R.B Montgomery

# Oceanographic Instrumentation

A conference held at Rancho Santa Fe, California, 21–23 June, 1952 under the sponsorship of the Office of Naval Research

*EDITORS:*

John D. Isaacs
Columbus O'D. Iselin

W.H.O.I.
Archives

Division of Physical Sciences
**National Academy of Sciences—
National Research Council**
publication 309

SHOUT
SHARE
IT

Given in Loving Memory of

***Raymond Braislin Montgomery***
*Scientist, R/V Atlantis maiden voyage*
*2 July - 26 August, 1931*

*******

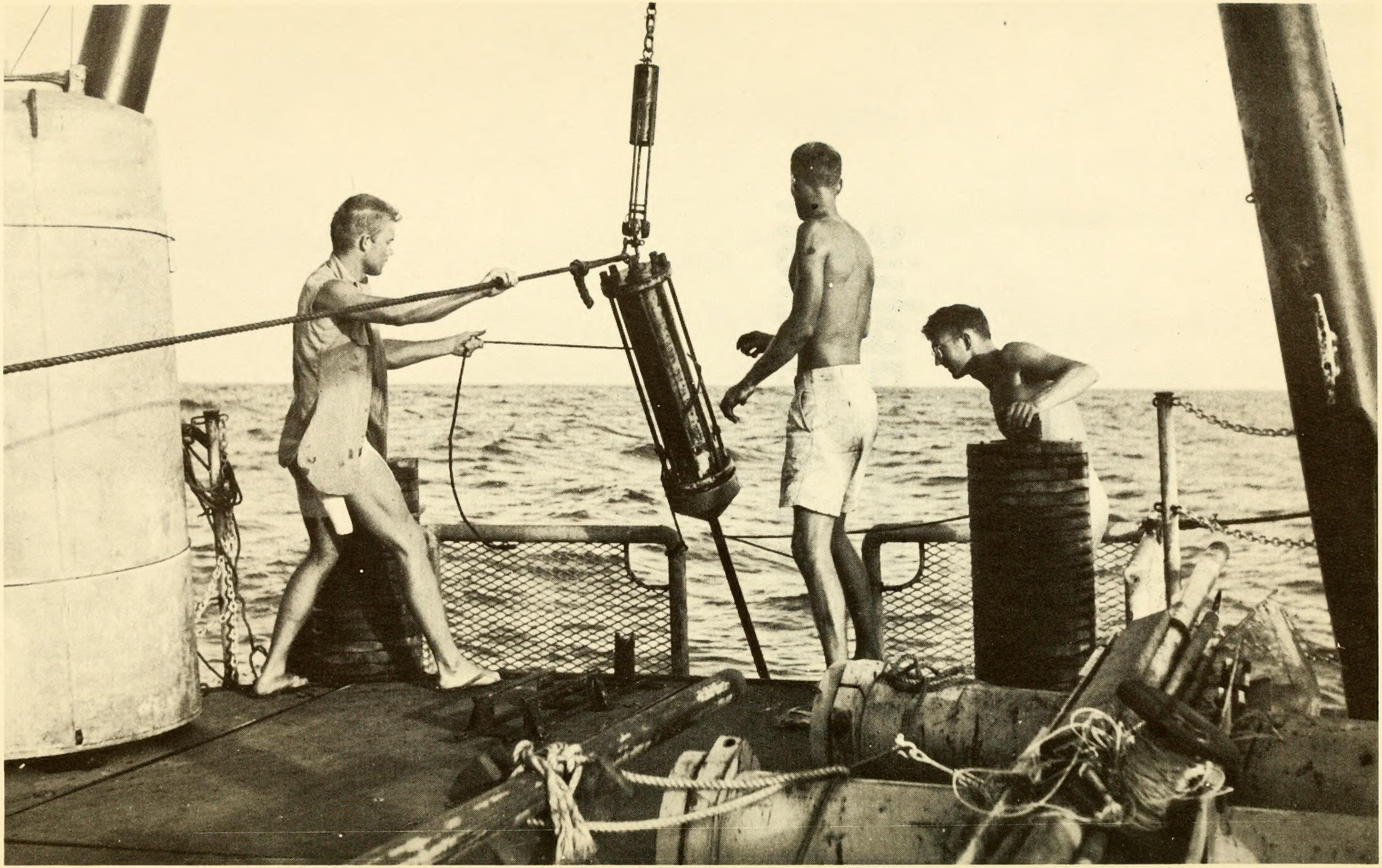
*Woods Hole Oceanographic Institution*
*Physical Oceanographer*
*1940-1949*
*Non-Resident Staff*
*1950-1960*
*Visiting Committee*
*1962-1963*
*Corporation Member*
*1970-1980*

******

*Faculty, New York University*
*1940-1944*
*Faculty, Brown University*
*1949-1954*
*Faculty, Johns Hopkins University*
*1954-1961*
*Professor of Oceanography,*
*Johns Hopkins University*
*1961-1975*

MBL/WHOI
0 0301 0093473 3

# Oceanographic Instrumentation



FRONTISPIECE. At sea launching and recovery of the bottom temperature gradient probe aboard a vessel of the Scripps Institution of Oceanography.

WHOI AO
Ise

DATA LIBRARY
Woods Hole Oceanographic Institution

# SYMPOSIUM ON OCEANOGRAPHIC INSTRUMENTATION

Rancho Santa Fe, California

June 21-23, 1952

Sponsored by the Office of Naval Research

Division of Physical Sciences
National Research Council

# PARTICIPANTS

ELBERT H. AHLSTROM
*U.S. Fish and Wildlife Service*

LLOYD ANDREW
*Navy Electronics Laboratory*

CLIFFORD A. BARNES
*University of Washington*

WILLARD N. BASCOM
*Scripps Institution of Oceanography*

DAYTON E. CARRITT
*Chesapeake Bay Institute*

RALPH J. CHRISTENSEN
*U.S. Navy Electronics Laboratory*

GEORGE L. CLARKE
*Harvard University*

B. K. COUPER
*Bureau of Ships*

ROBERT S. DIETZ
*U.S. Navy Electronics Laboratory*

CARL H. ECKART
*Marine Physical Laboratory*

RICHARD H. FLEMING
*University of Washington*

ROBERT G. FOLSOM
*University of California*

THEODORE R. FOLSOM
*Scripps Institution of Oceanography*

JEFFREY D. FRAUTSCHY
*Scripps Institution of Oceanography*

R.C. GIBBS
*National Research Council*

BRUCE C. HEEZEN
*Lamont Geological Observatory*

J. B. HERSEY
*Woods Hole Oceanographic Institution*

JOHN HOLMES
*Woods Hole Oceanographic Institution*

JOHN D. ISAACS
*Scripps Institution of Oceanography*

COLUMBUS O'D. ISELIN
*Scripps Institution of Oceanography*

WILLIAM V. KIELHORN
*Office of Naval Research*

E.C. LAFOND
*U.S. Navy Electronics Laboratory*

LEONARD N. LIEBERMANN
*Marine Physical Laboratory*

JOHN LYMAN
*U.S. Navy Hydrographic Office*

WALDO K. LYON
*U.S. Navy Electronics Laboratory*

THOMAS A. MANAR
*Scripps Institution of Oceanography*

WILLIAM G. METCALF
*Woods Hole Oceanographic Institution*

R. B. MONTGOMERY
*Brown University*

WALTER H. MUNK
*Scripps Institution of Oceanography*

HAROLD E. NASH
*U.S. Navy Underwater Sound Laboratory*

ROBERT G. PAQUETTE
*University of Washington*

FRANK PRESS
*Lamont Geological Observatory*

D. W. PRITCHARD
*Chesapeake Bay Institute*

RUSSELL W. RAITT
*Marine Physical Laboratory*

A. C. REDFIELD
*Woods Hole Oceanographic Institution*

ROBERT O. REID
*A. and M. College of Texas*

ROGER REVELLE
*Scripps Institution of Oceanography*

NORRIS W. RAKESTRAW
*Scripps Institution of Oceanography*

GORDON A. RILEY
*Bingham Oceanographic Laboratory*

FRANK E. SNODGRASS
*University of California*

JAMES M. SNODGRASS
*Scripps Institution of Oceanography*

ROBERT J. URICK
*Naval Research Laboratory*

ALLYN C. VINE
*Woods Hole Oceanographic Institution*

WILLIAM S. VON ARX
*Woods Hole Oceanographic Institution*

ALFRED H. WOODCOCK
*Woods Hole Oceanographic Institution*

J. LAMAR WORZEL
*Lamont Geological Observatory*

FRED ZIEZENHENNE
*University of California*

## FOREWORD

The papers presented in this document represent the results of a symposium on oceanographic instrumentation held at Rancho Santa Fe, California on 20 to 23 June 1952.

This symposium is one of a type which the Office of Naval Research and the National Academy of Sciences-National Research Council have at intervals jointly sponsored in various of the earth sciences. It has been the plan of these meetings to include as participants only those workers who are deeply engrossed in the subject at hand so that there may be assembled in one place, or in one published document, the current agreements or disagreements on problems of a particularly difficult or timely nature.

We regret that it has been necessary to hold these meetings in places of limited access, and to restrict the attendance to participants. Experience has proved, however, that large audiences are distracting as are centrally located points of convening where there are always many things to do in addition to attending a conference. Thus, mountain tops, resorts out of season, and the desert have been chosen as locales for these working symposia.

Throughout the past 10 years the subject of oceanographic instrumentation has always been important and timely, and it is likely to continue as a growing field of endeavor with new electronic and mechanical devices being invented almost daily. It is important to oceanographers that these instruments do not become lost or forgotten in the press and flow of new and better equipment. Much of the instrumentation does not find its way into the normal scientific literature. Practically all of its description is hidden away in reports of limited distribution. It is hoped that this publication will in part rectify the situation and make available to a large audience the results of several years of oceanographic instrumentation development.

The Office of Naval Research appreciates deeply the friendly cooperation of the National Academy of Sciences-National Research Council and the excellent manner in which the Rancho Santa Fe symposium was arranged. Our special thanks are extended to John Isaacs of the Scripps Institution of Oceanography and C.O D. Iselin of the Woods Hole Oceanographic Institution for the tedious and time-consuming task of collecting and editing the papers. We are indebted to Dr. R.C. Gibbs and John Coleman for the detailed work of organizing the meeting and supervision of publication.

Gordon G. Lill
Geophysics Branch
Office of Naval Research

# PREFACE

The long arm of the oceanographer is his ship, his steel cable is his sinew, and his instruments his fingers groping into an unknown that covers three-quarters of this earth. It is not surprising, therefore, to find the subject of instruments to be a lively one in the oceanographic fraternity. These explorers who look for more than they can see, listen for more than they can hear, and reach for more than they can encompass, seldom meet without a discussion of instrument limitations and needs and an exchange of experiences and ideas. Nevertheless, the very distance that separates the oceanographic institutions of this country, alone imposes a barrier to effective communications and the mutual exchange and critical review of new techniques and developments. For this reason, the editors of this symposium, speaking for the staffs of their institutions and, we are sure, for all the participants, wish to convey their appreciation to the National Research Council and to the Office of Naval Research for their sponsorship of the Symposium on Oceanographic Instrumentation. They speak also in appreciation of the physical arrangements which provided at the Inn of Rancho Santa Fe an environment free from distractions and conducive to the presentation and exchange of the ideas partly recorded in the following pages and partly unrecorded in the informal discussions and conversations stimulated by the group's contiguity.

In assembling the several papers and discussions, the editors have attempted to retain some of the flavor of the meeting. Many of the discussions were submitted as discourse, where possible, and the give and take of the meeting has been retained. Although this results in some unevenness of style among the contributions, this irregularity is of lesser importance than the ingredient from which it stems. Much information could not be presented by the authors because of military classification. Some information has been added in the form of footnotes when arising subsequent to the symposium. Other later material has been added as appendices where necessary for completeness.

It is regrettable that so much time has been required to complete the task of compiling, editing and publishing these proceedings. In part this has been due to the distance that separates the editors and the many individual contributors, in part to the press of many activities, and in part to the necessity of transmitting copies of papers to the authors and to the discussants and successively returning the copies incorporating corrections and comments. Without exception the contributors to this symposium have been prompt and cooperative. Thus the editors must shoulder the greater part of the blame for the delay.

The interim has not been without consolation, however, for it has seen the foresight of the sponsors already vindicated in some measure by the fruition of a number of the ideas delineated in the following pages. Nor has this period of apparent inaction been one of continuous repose. The task of coalescing the papers has not been trivial. There is ample evidence in these proceedings that oceanographers are an ingenious breed of independent mind. In part this results from the necessity of their improvising to meet new problems aboard ship during long periods at sea when facilities and opportunities for collaboration are limited. Even more, it stems from the fact that the sea recognizes none of the bounds of the established disciplines, but rather demands from its students a flexibility and diversity of method that characterize their work and are reflected in their writings. The reader will thus find that the authors often cut across fields and the discussant, when confronted by inclusive ideas of the author, must often respond by giving record to his own solution.

Finally, the editors would like to express their gratitude to the many members of their own fellow institutions and the National Research Council, who have rendered invaluable assistance in preparing the manuscript for publication. Our inability to list all the names of those who aided in preparation of illustrations, compiling the index, checking references, typing and retyping and the many other necessary tasks in no way should be taken as a lack of appreciation for the significance of their contribution. Without their effective and unrewarded help this report would not be available.

John D. Isaacs

Columbus O'D. Iselin

# CONTENTS

List of Participants ii

Foreword iv

Preface v

I. CONSIDERATIONS OF OCEANOGRAPHIC INSTRUMENTATION
John D. Isaacs, *Scripps Institution of Oceanography* 1

DISCUSSION:
Roger Revelle, *Scripps Institution of Oceanography* 10
Allyn C. Vine, *Woods Hole Oceanographic Institution* 11
Robert G. Paquette, *University of Washington* 12

II. MEASUREMENTS OF THE OCEANIC CIRCULATION IN TEMPERATE AND TROPICAL LATITUDES
William S. von Arx, *Woods Hole Oceanographic Institution* 13

APPENDIX 21
DISCUSSION:
Columbus O'D. Iselin, *Woods Hole Oceanographic Institution* 28
Richard H. Fleming, *University of Washington* 28
D.W. Pritchard, *Chesapeake Bay Institute* 29

III. BIOLOGICAL INSTRUMENTS
Elbert H. Ahlstrom, *U.S. Fish and Wildlife Service* 36

DISCUSSION:
Gordon A. Riley, *Bingham Oceanographic Laboratory* 46
George L. Clarke, *Harvard University* 47

IV. OCEANOGRAPHIC INSTRUMENTS FOR MEASURING TEMPERATURE
Allyn C. Vine, *Woods Hole Oceanographic Institution* 55

DISCUSSION:
E.C. LaFond, *U.S. Navy Electronics Laboratory* 65
Robert O. Reid, *A. and M. College of Texas* 66
Theodore R. Folsom, *Scripps Institution of Oceanography* 67

V. GEOPHYSICAL MEASUREMENTS
Russell W. Raitt, *Marine Physical Laboratory* 70

DISCUSSION:
Frank Press, *Lamont Geological Observatory* 79
J. Lamar Worzel, *Lamont Geological Observatory* 80

# CONTENTS

VI. SEA-ICE PROBLEMS

Clifford A. Barnes, *University of Washington* 85

DISCUSSION:

Waldo K. Lyon, *U.S. Navy Electronics Laboratory* 94
John F. Holmes, *Woods Hole Oceanographic Institution* 98
William G. Metcalf, *Woods Hole Oceanographic Institution* 98

VII. ACOUSTIC INSTRUMENTATION AS A TOOL IN OCEANOGRAPHY

J. B. Hersey, *Woods Hole Oceanographic Institution* 101

DISCUSSION:

R. J. Christensen, *U.S. Navy Electronics Laboratory* 111
Harold E. Nash, *U.S. Navy Underwater Sound Laboratory* 113
Leonard N. Liebermann, *Marine Physical Laboratory* 120

VIII. CONSIDERATIONS IN THE CONSTRUCTION OF OCEANOGRAPHIC VESSELS

William V. Kielhorn, *Office of Naval Research* 123

DISCUSSION:

John Lyman, *U.S. Navy Hydrographic Office* 129
B. K. Couper, *Bureau of Ships* 132
Allyn C. Vine, *Woods Hole Oceanographic Institution* 133

IX. WAVE MEASUREMENTS

Frank E. Snodgrass, *University of California* 139

DISCUSSION:

Walter H. Munk, *Scripps Institution of Oceanography* 159
Carl Eckart, *Marine Physical Laboratory* 161

X. CHEMICAL MEASUREMENTS

Dayton E. Carritt, *Chesapeake Bay Institute* 166

DISCUSSION:

Clifford A. Barnes, *University of Washington* 186
Dayton E. Carritt, *Chesapeake Bay Institute* 188
Norris W. Rakestraw, *Scripps Institution of Oceanography* 189

XI. METHODS OF EXPLORING THE OCEAN FLOOR

Robert S. Dietz, *U.S. Navy Electronics Laboratory* 194

DISCUSSION:

Bruce C. Heezen, *Lamont Geological Observatory* 200
Jeffrey D. Frautschy, *Scripps Institution of Oceanography* 205
Roger Revelle, *Scripps Institution of Oceanography* 206

XII. AIR-SEA BOUNDARY PROCESSES

Walter H. Munk, *Scripps Institution of Oceanography* 210

DISCUSSION:

Robert O. Reid, *A. and M. College of Texas* 213
Alfred H. Woodcock, *Woods Hole Oceanographic Institution* 219
R. B. Montgomery, *Brown University* 220

# CONSIDERATIONS OF OCEANOGRAPHIC INSTRUMENTATION

John D. Isaacs

We are here to discuss a great and curiously diverse assemblage of ships, dredges, thermometers, intricate electronic devices, plankton nets, hydrophones and water samplers. This list is diverse, yet it includes only tools and instruments -- tools that permit us to reach where we otherwise could not reach; and instruments that permit us to see or hear where to our unaided senses all is black and silent. And these two are fused by singularity of purpose -- to disclose the nature of the oceans to the mind of man.

We plan to consider these extenders and amplifiers of our motor and sensory abilities as they are brought to bear on an understanding of the oceans. Yet they are only temporal links between the two basic realities, the sea and the mind of man. We cannot consider instruments as an isolated problem more than we can consider the ocean isolated, without top nor bottom. We first must consider the characteristics of the two fundamental systems between which instruments must weld a link. The basic matches are not of compression waves between a crystal and water, not of magnetic waves between steel and the sea, but between man's mind, together with its sensory outgrowths, and the realm toward which his compelling curiosity is directed. The physical linkage of an instrument to the sea usually is concurrent with its operation, but before final presentation of its information to the mind many complex steps may be interposed, often including manual transformations which we must consider part of the link, that is, part of the instrument. Throughout this discussion I will consider the presentation of the sea to the mind in two intergraded parts, first a presentation of data to individuals who can relate the data to known or partly known unit concepts to be secondly presented to other individuals for inclusion or consideration in a more general concept. Thus the reading of the reversing thermometer is only the primary presentation and the completed dynamic topography a much more inclusive presentation. Each grade of presentation has its peculiar problems. Nevertheless, the steps between the sea and final presentation to the mind are all a part of the instrument and one goal of instrument development must be to include more and more of the steps of presentation in the mechanism. The STD (Salinity-Temperature-Depth Recorder) is an example of this trend.

First, let us consider the relationship between an understanding or concept and the instruments upon which its furtherance must depend. Can we say that the basis of all understanding is experience? I recently have become convinced of a point which others have understood much more easily. Somehow it had seemed to me that there was a basic difference between such understanding as, for instance, that light intensity varied with the inverse of the distance from the source and such concepts as the Pauli Exclusion Principle which sets forth the conditions under which an electron can occupy a position in an atom. The first case fitted into my general concept, seemed to be naturally logical and

---

* - Contribution No. 678 from the Scripps Institution of Oceanography

based upon a geometric process which needed little elucidation, whereas the second seemed highly empirical and based upon a fictional model derived from a special group of described facts, quite independent from the general concept. Obviously however, there is no difference between the reality or bases of these two pieces of understanding but only in the degree of experience necessary to establish them and in the degree to which they are related to a more general and central model. It is apparent that intelligence without appropriate experience has no opportunity to generalize the principle of conservation necessary for the principle of light intensity to seem simple and logical. And further, neither of these principles are more empirically based than the conception of the digit one, which is a concept no intelligence would obtain without experience, although the experience necessary is extremely simple and the concept seems inherent.

Let us say, therefore, that, regardless of the degree of intelligence, understanding is non-existent without experience. To a certain level of understanding, our unaided senses and motor abilities are capable of supplying a great fund of experience. For instance, in the case of the intensity of light, a spot of light shining through a hole, our hand moved closer or further from the hole and our eyes to inspect the illuminated area are all the instruments and tools and information which are necessary for our mind to formulate and roughly generalize the relationship between distance from a light source and intensity. This is far from the case for the Pauli Principle, for no intelligence could arrive at this concept with our unaided senses, and the instrumentation necessary to accumulate the supporting information is incredibly complex.

What now is the relationship between the development of knowledge and instruments? Historically they leap-frog one another in a somewhat haphazard fashion. Intelligence, with a background of understanding and the ability to theorize, generalize, and to extrapolate, thirsts for more information while instruments lag; then in one swift step, newly developed instruments begin to feed information to the intelligence much more rapidly than it can be assimilated. Sometimes this is information which substantiates expectations, often the disclosures of the prototype are much more complex than predicted by the mental model, and hence many great and surprising disclosures (often in a field foreign to the investigation) have been made by instruments that very generally probed into the unknown and accepted all information about the particular subject rather than those that by preconception disregard information that was not predicted in the mental model.

Thus we see intelligence accumulating understanding and desiring more, instruments extending our senses and providing more information than intelligence can immediately explain, and proceeding thus with protracted periods of stagnation then dizzy advance -- toward a better disclosure of the universe.

Let us consider in some detail the elements of this disclosure and the pecularities of the components.

The mind, which is characterized as the repository of the intelligence, continuously attempts to construct a rational model which will explain all observations, then tests the model.* It attempts to provide an explanation for the greatest number of facts with the simplest model. This process is greatly saving in total effort. Persons with defective minds, for instance, can be taught to make change for 84 cents from a dollar, 83 cents from a dollar, etc., each as a separate problem requiring an individual effort of the memory. Many such individuals can recall a vast number of accurate solutions yet are entirely helpless to solve those problems which fall outside their memory and may be thrown into confusion by the problem of 83 cents from $1.01. The normal mind devotes little effort to the problem of making change in comparison with this defective mind as the normal mind only needs to understand a general concept. Part of the problem of arriving at a fuller understanding of any system involves the mental manipulation of generalized models rather than a memory of unexplained details. I am sure that each of us recognizes a consciousness of reduced effort when the conception of a mental model explains, generalizes, and permits us to forget a previously "unexplained" mass of detail.

---

* - I am impressed by different racial attitudes on this point. Primitive races and even advanced races like the Chinese display a great compulsion to construct the model but little inclination to test it. Persons with certain religious attitudes not only fail to test their concept but actively avoid such tests.

Instrumentation, therefore, is most effective when it is capable of presenting proper and sufficient information to permit subsequent generalization into models, rather than when it is capable of presenting only a mass of data. The mixed facies of radiolaria, near bottom turbidity, deep bottom ripples, manganese nodules, etc., are at present only a syndrome of isolated facts indicative of our deficiency of understanding of deep sea processes. The understanding will be aided by instrumentation that can present the proper information in such a way that these facts can be fitted into our concept. The difference of presentation of data of the wire sounding machine and the echo sounder is an excellent example. The wire sounding machine was capable of presenting isolated data which could fit only into the largest and least complete model, with anomalous soundings as irritating and unexplained facts. The echo sounder can, in effect, presents a seamount, a trench, or a swell as a unit, relative to some intensively studied example, and permit the thought to handle the more complex unit with reduced effort. Understanding comes much more rapidly from these generalities. How much can be done with a vast memory of soundings across the ocean, compared with the knowledge that "here the ocean is pimpled with seamounts, here great trenches parallel steep mountainous coasts, and here are great level plains".. The entire sea must eventually become a unit model which can be applied with understanding to other seas of the universe in space and time. Thus the Revelles, Iselins, Eckarts, Munks, and Sverdrups, dealing with complex models as units rather than with details are left free to associate these into even greater concepts for greater understanding.

Let us look for a moment in more detail at the mode of growth of this mental model. Its advancing fronts are mainly qualitative or descriptive, its central core is quantitative and general. Satellite concepts, some in advance phase and not yet incorporated in the central core, exist in more or less remote areas.* Qualitative data often are sufficient for the development of the front, but for a test of this model it is necessary for quantitative data to be obtained. The multitude of individual processes are then generalized into a principle or mathematical statement which substitutes, as a simpler process, for the complex processes in the prototype. When it becomes necessary to push further and utilize the principles discovered for support of further understanding, considerable perfection frequently is required, second and higher order terms must be investigated, and these in turn must be tested.

Thus we have in the development of some portion of our understanding, three indistinct and intergraded phases: the qualitative phase (the ocean is deep, cold, wet, salty, and dark); the early quantitative phase, where mean depths, rough temperature distribution, light penetration, etc., are adequate; and a later quantitative phase where the thermocline, earth's heat, evaporation, etc. must be quantitatively determined.

---

* - Some concepts apparently are doomed to an eternal orbit as dead satellites. The study of dinosaur footprints in Connecticut (a complex taxonomy) probably never will be incorporated significantly into our understanding of the Mesozoic.

The requirements of instruments depends clearly upon the phase of the investigation. Instruments for the determination of second order terms normally cannot accept general information but must be considerably specialized. It therefore is contrary to normal development to employ specialized instruments in the qualitative phase, where information may be lost, and it is obviously inadequate to attempt to obtain second order information from the use of instruments designed for an earlier stage of understanding. Particularly it is dangerous to continue to employ early quantitative techniques far into the quantitative stage if they supply only masses of data in too great detail for the general concept.

The state of understanding greatly influences the requirements of sensory presentation. Early in the qualitative phases, the most general and broadly receptive sensory presentation should be employed. I believe that it is an error to present visually an analyzed harmonic frequency curve before one understands the source of the signal or has even heard it. This type of over-instrumentation is common and stems from the belief that our only quantitative sense is our visual sense and that the development of instruments in the final quantitative stage must present their data as an image. In the qualitative exploratory stage, however, the advantages of the other senses should not be overlooked. Let me present an example. Workers, exploring a new field of ocean phenomena, employed an extremely narrow band pass filter in a visual presentation, because of a mistaken idea that background was random. The signal could not be detected from the background because the additional information which would have permitted separation was eliminated from both the signal and the background. Later investigators using a much simpler system which presented all information audibly not only had instant success in detecting the signal but discovered an unusual and fascinating background that opened an entirely new field of processes in the sea.

Let us now consider the characteristics of the senses of mankind, as a link between the instrument and the mind.

The human mind, in the process of evolution, has pushed out an extremely complex series of receptors to learn about its environment and has developed for reception of their stimulae such remarkable interpreting mechanisms that some of these constitute special senses in themselves. Our senses actually include then, portions of the brain that assist and augment our senses by interpreting, recalling, associating, and transmitting. This is the fundamental control about which all presentation through the receptors must be designed. As an integral part of our senses, the limitations of the interpreting mechanisms are the limitations of the whole.

We are continually aware of some of our senses and capacities, others accomplish their design so subtly that their existence is hardly recognized. The kinesthetic image, for example, provides a continuous sensory picture of the position of any portion of our body, and we can demand from it further and more detailed information about any point. Perhaps a mention of this sense is not so inappropos as it might seem, for it vitally contributed to man's first ability to employ tools -- as man possesses a unique extension to the kinesthetic sense which allows him to extend this sense to the tools that he holds. Tap a pencil on the desk and you will discover that your nerves have been extended to its tip. From the nerves extended in the axeman's blade, to the feel of a helmsman for his ship, and to the radio-chemist's servo-manipulation, this curiously inconspicuous sense has extended man's physical accomplishments.

As to the mode of presentation of information to the mind, we are so strongly conscious of our visual sense that a presentation to our sight, regardless of form, often is unquestioningly accepted as the ultimate completion of an instrument linkage. "Seeing is believing" is a mere statement of the reliance that man places on his sight for we accept the evidence of our sight over the evidence of all of our other senses. Ordinarily we will accept the evidence of any other sense to the point where it conflicts with our sense of sight. The concentration upon purely collecting devices in a young science like oceanography, partly is an expression of the amount of knowledge which can be drawn through visual inspection of samples. Yet the sense of sight, with the bountiful information presented to it, interprets only part of that information, while the ear, with a comparative paucity of information analyzes it in much greater detail. I like to think of this as a development from the requirements of recognition. To primitive man the image of a lion ordinarily was sufficient for recognition and color was almost redundant but a sense of hearing which conveyed only the pure mean tone of a lion's roar would be inadequate, indeed. And hence we have developed the incredible capacity which allows a musician to recognize instantly a symphonic passage, to identify positively the conductor, and very likely to recognized the makes of some of the instruments. If our color sense had only part of this frequency resolution, a diffraction grating would be a mere laboratory curiosity instead of the bottleneck in the study of atomic states. Or if we possessed in vision the time sequence memory that in hearing allows the ordinary individual to recall several hundred thousand notes in time sequence and duration, the committing to memory of the soundings, temperatures and salinities on an expedition would be commonplace. As oscilloscope presentation is valuable, yet in many cases we could receive more information more rapidly with more understanding and better memory if we heard it. These are important considerations in the early exploration phases when we are dealing with details rather than concepts.

I belabor this point somewhat because of a conspicuous tendency on the part of instrument designers to consider that the presentation to the sight is the final goal without regard to the stage of the investigation, possibilities of the other senses and, particularly, without regard to the peculiar limitations of our visual sense.

We must not overlook such facts as that a demanding test of a wake detector is whether or not a man can smell diesel fumes at the site of suspected contact. I do not doubt that if we could add one stage of amplification to our olfactory sense we could track a snorkeling submarine around the world or locate regions of high plankton productivity from an aeroplane fifty miles downwind.

It commonly is believed that our visual sense contains our only quantitative power. Actually this is untrue, and the visual sense possesses only the power that other senses possess, an ability to make comparison with a standard. However, these standards are so simple and so common (scales on a thermometer, rules, divisions on a chart) that we accept them as an inherent capacity of our visual image. Actually the unique capacity of our vision is the power of interpolation, for on any grid we can mentally superimpose a finer grid for accurate interpolation. This is a power that other senses have only to a slight degree. The degree of this power greatly affects the number of standards required. Thus a method such as a colorimetric determination of alkalinity by standards, suffers from our mental inability to superimpose a grid of color standards between the provided standards and to interpolate the actual value. Such a method soon gives way to a visual linear presentation. Hence, audible records are "analyzed" for presentation to our sight, hardnesses are shown on a scale of a hardness tester, and in every way the burden of presenting quantitative evidence to the mind is thrown upon the image sense.

To summarize these rather rambling ideas on the senses, I feel that we are missing some important opportunities in presentation of information. We must consider the special capacities and limitations of the senses. Our visual sense has extremely poor memory for most time sequences and time integrations, but is capable of absorbing and recalling innumerable complex three dimensional figures. It has incredible capacities to recognize shapes, it can recall without effort innumerable car body types. I can conceive that an annual record of thermal structure can be absorbed in one effort of the mind, if presented as an isometric view of a three dimensional figure or even as a "thumb movie" of rapidly riffled small diagrams. Yet we present the mind with unrecognizable dots in time and space, or complex tables of data, from which we must mentally derive trends or plot curves. This failure to consider optimum presentation is also conspicuous in primary presentation. When we need to detect correlating pips in a strong random background, we ask the eye to pick out these rare points by memory in time sequence, a task which it performs very poorly. Yet we possess an analyzing mechanism of tremendous power operating between our two eyes that can neglect all non-correlating points and cause the correlating ones virtually to pop from the screen. Can we afford to besiege the mind with tables of data when in one effort a three dimensional expression can be absorbed?

Lest you are becoming apprehensive that I have forgotten the subject of this symposium, let us consider instruments.

They are expressions of the fact that man's mind can conceive of more than it can perceive. They are extenders of our senses and link the mind more closely to the universe. But they are mechanisms, and mechanistically we might say that they sample matter or energy and present their findings, either quantitatively or qualitatively, to our senses. This presentation may or may not be transformed in some way. Non-transforming samplers are called collectors, a great class of scientific instruments that are borderline between true tools and instruments. As already pointed out these are of greatest value in the broad qualitative phases of an investigation. They must always retain an important place in an investigation, yet they should evolve in a manner commensurate with the growth of basic concepts in order for their information to be fed to the mind most efficaciously. Collecting instruments produce much detail and as a consequence tend to stultify an investigation by sheer mass of information The plankton net can be discussed here, for while its information is invaluable for isolated intense, and specific investigations, when the broad descriptive phases of the investigation have been completed, it is essential that methods of analysis be developed that can present the planktonic component of the sea in the least detailed yet most informative manner. This would be a presentation in which the breakdowns in time, dimension, and type were no larger nor smaller than their significant magnitude in the sea at the degree of complexity of the required extension of our concept. For example, if a plankton collection is intended to determine available food substances, we should not develop instruments and methods for greater than significant spacial and taxonomic resolution but rather integrate the sample spacially over the typified area, and analyze it for total organic carbon, by phyla and size. The resultant information would be much more conducive to an enhanced concept of productivity than are the multitudinous taxonomic records obtained today. New biochemical techniques must be developed before such analysis is possible. Chromatographic methods, such as Buzzati's, give hope for the ultimate development of such a system of broad analysis. Other collecting methods require similar revisions including phytoplankton, sediment, and salinity collectors. For special detailed investigations of variability, microstructure, productivity of specific forms, or distribution, present collectors must be altered in the opposite direction, of course, but such detail presently is not required for fundamental advance of our general concept unless the organisms be valuable as tools for following broad processes.

Collectors are greatly limited in the nature of the data that they can present. Their information principally is that of standing crop and it is only with difficulty that processes or dynamic states can be revealed by collecting techniques. In fact, our glaring deficiency in instrumentation at present is an almost complete lack of methods of understanding a dynamic state. Temperatures, salinities, populations, nutrient concentrations, and transport all are measurements of standing crop of matter or energy. The measurement of the dynamic state, so essential to an understanding of the sea, awaits novel methods of evaluation.

All samplers, other than collectors, transform the sample into some form by which it can be linked to our senses. In some instruments the sample is not transformed in its basic nature but altered or amplified and directly presented to the sense that originally could have received the unaltered stimuli. Optical instruments commonly fall into this category, as do calipers. Other transforming samplers transform the sample into some other energy form which is presented to the senses in a qualitative or quantitative fashion. An ordinary audio amplifier is an example of the qualitative transforming sampler. Quantitative transforming samplers are our common measuring instruments and almost invariably present their information to our vision, as discussed before. Some measuring instruments present only one measurement for each operation. These are called gages. Some present their information continuously but do not record. These are called meters or indicators. A typical modern measuring instrument produces a permanent record relating two or more wanted parameter of which one is frequently time; these are called recorders. Collectors are not alone in providing masses of data and recorders also are prolific. For instance, much of what I have said about plankton nets applies to wave recorders. A measuring instrument physically consists of elements for:

(1) Sensing (sampling)
(2) Transforming
(3) Amplifying and sorting
(4) Presenting

Certain thermodynamic principles inter-relate characteristics of materials and levels of energy. The sensing element normally is in itself a transformer utilizing such interrelations as are selected to be specifically affected by the desired factor. These effects frequently are named by the transformation involved, thermo-electric, thermal-expansion, magnetostriction, etc., however the longer-known relationships of compressibility, elasticity, etc., are no less transformers. There is invariably an effect of other changing unwanted factors which, if significant, must be introduced as corrections into the system at some point prior to final presentation.

The important characteristics of the sensing element are that it recover a sample with proper integration or resolution in space and time that is large enough to permit the presentation, yet not so large as to alter the nature, quantity, or distribution of the energy or material sampled. Nor should the non-measuring or structural portion of the instrument alter the characteristic of the sample. Here we must guard against over-instrumentation. For example, it is obvious that a listening device may produce noise if the noise falls outside the band received. By some similar mechanism a dog is able to detect extremely small quantities of material by his olfactory sense, although he carries an unusually high olfactory background around with him. In addition to sensitivity to unwanted factors, the instrument also should not basically lose or confound information by responding to unwanted functions of the desired factor. This is a common failure of instruments, and some have persisted undetected for considerable time. An example is a transport measuring device which to a degree integrates $V^2$.

It is common for the sensing element to relate the desired parameter to electrical energy or mechanical energy. This is then "amplified" by adding quantitatively related energy or by altering some characteristic so that it is outstanding. Normal vacuum tube amplifiers add quantitatively related electrical energy. Thermometers, balances, scales, and calipers accentuate position. Filters, feedbacks and a tremendous variety of components are interpolated in the energy path at this point, and are best discussed by others. I would like to state, however, that in the introduction of these into an instrument system there is the greatest need for discretion and common sense for here lies the opportunity to produce either light or darkness.

We might liken this part of an instrument to a small path through a meadow which is suitable for limited travel. The introduction of powerful machinery for its improvement can either turn it into a morass or into a highway depending upon discretionary powers of the workers.

We finally arrive at the medium toward which man's curiosity is vented --the sea. Here his instruments have evolved as a product of environment in as real a fashion as have the organisms of the sea.

It is interesting to consider the effect of the nature of the sea on instrumentation by comparing the characteristics and consequent instrument evolution in the case of the exploration of the physical realms of oceanography, geology, meteorology and astronomy. The analogous and homologous instruments and tools in these realms frequently resemble one another so little as to be almost unrelatable. A discussion of this is interesting but let us consider only one example of analogous instruments for transport measurement: in oceanography, the reversing thermometer and Nansen bottle; in meteorology, the barometer; in geology, topographic surveys; in astronomy, instruments of spectroscopic doppler and photography. The same also is true of the homologous instruments for instance, the physical probe: - the lead, cable, and winch in the sea; the free balloon or rocket in the atmosphere; the drill and string of tools in the earth; and for astronomy, only the implications of hydrazine hydrate.

First, some things floated and some sank in the ocean and because of the ocean's intermediate density man early devised tools to move upon its surface and to probe its depth. The students of the other media did not have this singular advantage, but the oceanographers, like happy natives with a bountiful provender, have been content with their initial tools and have only under compulsion utilized techniques of exploration that were borrowed in principle from those students of nature less fortunately endowed, and who were pressed to develop other exploratory methods. I believe that we still are somewhat circumscribed by our ships, line and lead.

Second, the ocean is large, and man could explore only small parts of it that were immediately accessible. Exploration of the larger areas still remains in the descriptive and roughly quantitative phase. This led to early intensive investigations of small areas to a detail which was not justified in the general understanding of the time. The size of the ocean demands that we exercise care in its exploration and early generalize concepts of processes so that they can be recognized with the minimum of data. This requires intensive but guided investigation of limited areas to arrive at an understanding of the significant processes there so that this unit concept can be understood with appropriate alterations determined by a minimum of data when it is encountered elsewhere. Thus, instruments which can present a process by simplified criteria so that it can be related to a more intensively studied example are the most valuable. Intensive and indiscreet data-taking in the absence of some unit concept may be useless. $C^{14}$ determinations may reveal upwelling far more effectively than more complex criteria.

Though the sea is large, man's instruments are small and much difficulty ensues from measurements of variability that is not significant in the process under investigation. Integrating instruments appear to be very valuable where larger processes are being investigated, SOFAR signals, seismic exploration, drift instruments and high-speed samplers can give us a much clearer representative of larger processes than can a great number of more highly resolved measurements.

As a result of the early development of many oceanographic methods in restricted areas, much detailed information was obtained. As these methods were extended to greater areas, as much or even more detail was considered necessary. We must realize that we not only do not see the "woods for the trees" but are blinded by the leaves, and major progress will not ensue solely from initiating study of their histology but also from the development of methods of pushing them aside.

Third, the sea to most people is inhospitable and man concentrated much effort on his ships. His instruments as they developed tended to be rugged and more a product of the seaman than the scientist. Data taking was slow and difficult, and there has never been a great contribution of amateurs as enjoyed by astronomers, meteorologists, and geologists. The amateurs of oceanography have been drawn from a special class of seagoing people, and although this has contributed freshness to development, it has not brought the wide range of experience that has been brought by amateurs in other fields. This inhospitability and the size of the medium have made investigations very expensive and have consequently limited the total effort.

Fourth, the sea was dark and consequently mysterious; man knew that he saw only dim shapes below him, and their activities were to him a closed book. It was not so with birds and the clouds. The fact that the subject is mainly obscured from our vision has had a profound influence upon our methods, for we must probe blindly into the depths and visualize them only vicariously. It is this limitation that demands instruments that can supply us with oceanographic visualizations as readily as we can see clouds, rivers, mountains and trees. Fortunately, water transmits acoustic energy freely. Acoustic methods, underwater photography, and thoughtful presentation of other data in a manner acceptable to our minds someday may conquer this incubus.

I would like to speak further on such matters as the intimacy of the biological element with the oceans and why ornithologists are seldom meteorologists, but marine biologists are always oceanographers, but I have spent my time discussing the ships and why the sea is boiling hot and must leave the shoes, sealing wax, and flight characteristics of the pig for another time.

But before closing I have one more word. I know the exploratory phase of the study of the ocean will never be completed. I have much faith in the value of detailed examination of specific areas and generalized examination of greater areas, by proper instrumentation. But, I sincerely hope that instrumentation never becomes so sophisticated that it is unable to convey to us the unexpected and the inconceivable, for upon the acceptance of these depends the stimulation of our science and the better disclosure of our universe.

DISCUSSION: Roger Revelle*

From its beginning 75 years ago in the great British CHALLENGER expedition, the scientific exploration of the sea has tended to run in cycles. Each cycle of exploration has been initiated not only by the conceptual growth of new questions, but also by the development of new instruments and techniques. Throughout this period, however, one can trace a continuing trend - the increasing recognition of the unity of the earth sciences. We can not separate the history of the ocean from that of the earth as a whole, nor can we understand the processes now occurring in the ocean without taking into account what is happening in the atmosphere above us, and in the solid earth and liquid core beneath. Moreover, the scientific study of the earth as a whole is becoming evermore dependent on increased understanding of that part of the earth which is covered by sea water. Our definition of oceanography is thus gradually broadening to be simply: The science which is done at sea. A comprehensive discussion of oceanographic instrumentation should therefore include a description of the techniques of all the earth sciences, as modified for use above, or in, or under the ocean. From this point of view the present symposium may be regarded as a representative sampling, with the objectives of indicating the scope of the subject, the state of the art, and the lines of development.

The sea-going scientist labors under several disadvantages. First is the great disproportion between the area to be covered - almost three-quarters of the earth's surface - and the tiny number of full time professional workers. Second is the expense and difficulty of work at sea as compared to its rewards - the fact that man is a land mammal will be enthusiastically confirmed by any one who has been seasick in the small, oily and uncomfortable craft which are utilized as research laboratories by oceanographers. In this harsh environment the oceanographer must be as much seaman as scientist, and his instruments tend to be rugged and crude with attendant loss of precision and flexibility. Third is the stubborn opacity of the ocean to visible light - this has produced the paradox that we know more about the surface of the moon than about the topography of the ocean floor. Fourth, for the most part the oceanographer must make measurements, at a series of discrete points in space and time, of parameters which vary widely and often unpredictably from point to point and from time to time. Finally the oceanographer is largely denied the benefits of controlled experiment, that peerless tool of the laboratory scientist. His methods must be akin to those of the detective who patiently pieces together all possible clues in his attempt to reconstruct what has happened.

Surprisingly enough, however, many kinds of geophysical work at sea can be conducted with relative ease compared to corresponding investigations on land. In seismic work, consistent signals can be obtained through the sea floor out to distances of 60 miles with an 80 pound charge, and on occasion records up to 100 miles are obtained. On land, a distance of 10 miles with an 80 pound charge is considered very good. Measurements of heat flow through the sea floor, although somewhat difficult experimentally, are straightforward in interpretation because of the relatively uniform and constant temperature of the bottom waters over large areas of the oceans. In contrast, it is extremely difficult to obtain unequivocal determinations of heat flow on land because of migrating ground waters, uncertainties introduced by the circulation of drilling fluid in wells, and changing atmospheric temperatures. In magnetic and gravity measurements, the ability to use the sea surface as a reference plane and the simultaneous recording of a bottom depth profile considerably facilitate interpretation.

Moreover, experimentation does have its place in oceanographic investigations, particularly model experiments in which processes are studied on a reduced scale, and the conditions are varied, one by one, to establish a framework of analogy by which the full scale phenomenon may be better understood.

Perhaps more than any other scientific field, oceanographic research demands teamwork between scientists of different backgrounds and abilities. The classical method of experimental research in physics involves design of a critical experiment, a great deal of work in developing apparatus and in establishing rigorous control of the conditions, and a few careful measurements, all done by one or two workers. In geophysics it is usually necessary to take a large number of observations, both to obtain sufficient detail and to find a few simple situations where nature has "controlled" extraneous conditions so that we can gain understanding of underlying processes. An oceanographic instrument may therefore be used by many people who were not involved in its design and development, often for purposes quite different from those which motivated the designers. The recording echo-sounder is a pre-eminent example, for its use requires the background and insight of the geologist while its development demands the ingenuity and skill of electronic and mechanical engineers. Similar statements can be made about the whole range of oceanographic instruments described in this symposium, but a great deal of wasted effort results if the development of instruments and their use are not closely coordinated. Many ingenious gadgets have fallen into the limbo of disuse or have failed to achieve their full potentialities simply because of lack of mutual understanding between the developers and the users. It is sometimes argued that every research oceanographer should develop his own equipment, but I believe this would lead to a mass of spotty and unrelated observations which could not be synthesized into any significant model of the real earth. Even though it may violate the individualistic traditions of science, teamwork is the essential prerequisite for broad advances in geophysics.

DISCUSSION: A.C. Vine

All too often in conferences the papers presented are limited to a few of the technical accomplishments of the past year while discussion of the exciting techniques and problems of the future are relegated to conversation during lunch hour. Dr. Isaacs' paper has reversed the usual procedure in a way which provides a good omen for this symposium. In discussing his paper and the problem I can but echo his desire to concentrate on the novel approaches, the principles involved and the fundamental problems.

First, I would like to emphasize John Isaacs' statement that, historically knowledge and instruments have played leap frog with each other in a haphazard fashion. How often theorists and experimentalists have wasted their time arguing about which of their specialities is the most important when neither side knew if it was half a cycle ahead or behind the other. This is not to be interpreted that frequent and heated debates are not in order on whether oceanography needs a particular theory or a particular measurement most at any one time. In fact knowing most of the participants of this symposium I am sure the theoreticians will hold up their end of the discussion. Actually, the important thing is that the instrument designers, the experimentalists, and the theoreticians each do their work aggressively and well. Oftentimes great progress is made in a large scale straightforward approach right at the heart of the problem. Occasionally, this method hits an impasse and some clever unknown scientist gains the answer easily with an end-around play on a seemingly unrelated problem.

While we are discussing the problem of the comprehensive experiment versus the simple one, I want to call attention to a common looseness in our use of the words crude and precise. All too often one hears a latecomer in a field referring to the crude measurements which his predecessor made. Personally, I have a great regard for the early worker in a field, because I think that precise thinking and simple measurements have often had a larger scientific product than precise measurements and simple thinking. For example, I do not think measurements should be called crude if they accomplish their objective and materially add to our fund of knowledge. One should not be satisfied with inferior measurements but one must also be sure he doesn't concentrate on the difficult so much that he overlooks the apparent.

It is easy to divide any research work up into one of three classes:

1. The probing qualitative venture which usually is quite incomplete and generates more new problems than it solves.

2. The careful detailed study which answers important questions in a quantitative manner. Such measurements carry a ring of authority and are mile posts for future workers.

3. The in-between class which gives information but neither opens nor closes a problem.

This latter category is the dangerous one because it is the one into which we put most of our effort. It would, therefore, behoove us both as individuals and groups to do some soul searching on the types of instruments and problems we are going to undertake and ask ourselves, "Will it produce new problems, firm answers, or neither?".

DISCUSSION: Robert G. Paquette

It is refreshing to read Mr. Isaacs' unconventional discussion of the problems of measurement and exploration in the sea. He expresses basic philosophies which should be understood by explorers in any field. He relates the instrument to the senses from a viewpoint probably seldom before appreciated by an oceanographer, and presents a number of novel ideas which, if not immediately applicable, provoke progressive thought.

# MEASUREMENTS OF THE OCEANIC CIRCULATION IN TEMPERATE AND TROPICAL LATITUDES*

William S. von Arx

## OCEANIC CIRCULATION

At the present time the circulation of the oceans in temperate and tropical latitudes presents at least two rather separate aspects for study; the wind-driven system extending perhaps to the depth of the main thermocline, and a deep circulation system in which secondary effects of the wind-driven system and thermohaline effects may both be significant.

The wind-driven system has received the bulk of recent observational and theoretical study. In this work observers are equipped to make only fragmentary measurements of transient occurrences, while theoretical effort has been concerned mainly with the steady state, wind-driven circulation. It is difficult to reconcile these two kinds of results. Midway between them is the transient state which both groups hope to describe sooner or later.

Since physical intuition is acknowledged as an unsafe basis for the theoretical description of the oceans, it is necessary at first to describe transient conditions from observations. This description must be based mainly on direct observations taken simultaneously over a sufficiently large area to have synoptic meaning, and for a long enough time to distinguish the longer periodic variations from secular trends. It should be acceptable, at first, to average out the smaller scale turbulent processes so that only the bolder features of the flow pattern are revealed. Even so, this is a more ambitious program of observations than can be managed at present.

It seems evident that rather than new instruments we require new methods of observation which are adapted to the scale of the field problem. These methods should possess elements of speed and penetration to depths which far surpass those attainable from moving ships or aircraft for we would like to observe what is happening simultaneously at many places in the ocean and continue such observations for some time. Fixed ocean stations might be desirable. These might be designed either to record events against time, or report them at intervals.

In that the fine structure of the oceans cannot be inferred by interpolation, it also seems desirable to increase the density and simultaneity of observations from ships. This might be done by providing measuring devices which drift with the water to establish the continuity of the ocean structures between successive traverses by ships. These devices may also link observations from aircraft to the occurrences in the upper layers of the ocean.

---

* - Contribution No. 689 from the Woods Hole Oceanographic Institution.

In order to decide what is to be required of these instruments and how they may be designed, it seems necessary to review present ideas concerning some of the phenomena of oceanic circulation to see what may be observed.

## THE STEADY AND TRANSIENT STATES OF OCEANIC CIRCULATION

Stommel (1948) and Munk (1950) have offered a very satisfying theoretical description of a primary oceanic circulation system driven entirely by the mean zonal wind stress. Recently it has been possible to simulate qualitatively not only the graphical results of this mathematical model, but a number of secondary details of the ocean prototype in a rotating model (von Arx, 1952a). In these experiments a pattern of motion similar to the surface circulation of the ocean prototype has been produced in homogeneous water. The circulation develops almost immediately after a steady wind torque is applied, and coasts to a stop nearly as rapidly when the wind torque is removed. This result appears to support the growing impression that the superficial motions respond to a seasonal change in wind torque with little delay (Fuglister, 1951), but that large scale adjustments of the density structure take place much more slowly. The adjustments of the density structure may be effected by two mechanisms, or possibly three, having different times of response and different areas of influence. Since the Gulf Stream has been studied in some detail by many investigators, it serves especially well as a focus for discussion of these effects.

Seasonal variations in the transport of the Gulf Stream (Iselin, 1940) have been observed by the method of dynamic sections and are indicated to some extent in tide gauge records. Yet, in different authors' opinions, theoretical estimates of the rate of response of the density structure to a change in wind stress range from less than a decade to a millenium. In any case, it is longer than a season. Since the sun may not supply heat rapidly enough to change the volume of specifically light water in the Sargasso Sea by the amounts required to compensate the seasonal rate of change of wind stress, the compensating pressure gradients may be derived from a temporary deformation of the Sargasso water mass. Iselin has suggested (1940) that in periods of greater than average wind stress the horizontal extent of the Sargasso Sea may diminish in order that the pressure gradients may be temporarily increased through elevation of the free surface and depression of the main thermocline. These effects are thought to be reversed in the event of less than average wind stress. This response of the density structure would tend to distort the circulation pattern and cause it not to fit exactly within the geometry of the ocean basin. To compensate for this a change in volume of the Sargasso water mass is required which will take place at a secular rate determined by the ability of the sun to heat the added volume or by the ability of dissipative effects to cool enough water to restore the circulation to its normal geographic course. Were the rate of change of wind stress slow enough for the secular rate of accumulation or dispersal of specifically light water to keep in step, the volume of the Sargasso water might change while its horizontal extent remained constant.

While the elastic deformation of the whole Sargasso water mass may be rapid in comparison with the rate of accumulation or dissipation of specifically light water, there may be localized deformations of the pressure field that occur still more quickly; perhaps as rapidly as the response of the superficial circulation to a change in wind stress. A sudden increase in the velocity of the Gulf Stream would be accomplished by a corresponding increase in the Coriolis force. This would cause the motion to be directed to the right of the isobars and for water to be pumped toward the right side of the current and away from the left. In this manner a topographic trough may develop on the left and a ridge on the right of the current which would locally steepen the pressure gradient across the Gulf Stream and give rise to temporary countercurrents. There is evidence of such effects but it is too early to be certain of this interpretation.

While these effects may help to maintain a constant pattern of circulation under a wind pattern of variable intensity, there are anomalies in both the wind pattern and the flow pattern. In the equilibrium state it is considered that the climatological mean wind torque supplies the energy needed to overcome the frictional losses accompanying geostrophic motion across the pressure gradients. Frictional losses are thought to be greatest by far in the region of westward intensification of the current systems. Since the wind torque is accumulated over the whole ocean surface, the braking action in the zone of westward intensification must be very intense. Braking seems to occur not only as a result of water shearing over itself or against the continental boundaries, but by meandering and the shedding of eddies. The meander patterns in the westward intensified flow are well recognized (Iselin and Fuglister, 1948) (Fuglister and Worthington, 1951). The centrifugal accelerations accompanying meander curvature may sometimes amount to more than 15 per cent of the local pressure gradient acceleration (von Arx, 1952).

There may be other accelerations associated with the displacement meanders or their form drag as they move along the length of the current. Since the water masses on the right and left of the current are of different character, a meander represents a pair of waves moving in phase along both the right and left-hand density interfaces. The left interface separates the water masses having the greatest difference in density, so that waves on this interface, described theoretically by Haurwitz and Panofsky (1950), may dominate the wave pattern and motion. In order for a meander to grow or to progress it is necessary for the wave forms on both interfaces to remain approximately in phase and for the water masses adjoining the current to move about harmoniously as the waves pass. Through a combination of vertical and horizontal motions the water mass on the convex side of the current must withdraw, and that on the concave side must advance as a meander deepens. At the same time the reverse must occur as the meander progresses. This may give rise to characteristic circulation patterns in the adjacent water masses. It seems unlikely that with an inequality in the density differences on either side of the current the rate of progress of the waves along the borders of the adjacent water masses can be so harmonious that there will be no change in either the pressure difference across the current or of the width and depth of the current. Localized convergence and divergence of flow and accelerations of other kinds may influence the details of motion even if the system is broadly in geostrophic equilibrium. That is to say, the equilibrium state is not necessarily a steady one.

Finally, currents like the Gulf Stream are not driven primarily by local winds. The passage of storm centers across these currents and neighboring water masses may influence the results of direct current measurements near the surface and cause temporary departures from geostrophic motion, probably involving cyclic motion in inertia circles. These add many difficulties to the problem of relating field observations to the broad ideas that have been discussed, and suggest both the length of time observations must be carried on to obtain a fair sample and the detail that would be desirable in describing the transient state.

As a step to broaden the scope of observations, the tendency recently has been to measure the properties of the surface layer from ships moving at cruising speed. This present trend to rapid surveys with one or more ships is not likely to bear fruit of the necessary quality or quantity for study of the volume circulation unless ships can be made to sail faster and instruments can be devised for working at all depths at these higher speeds. According to present views, increased ship speeds exclude the possibility of apparatus being towed very much deeper than the 100 meter level.

## ANCHORED BUOYS AS OCEAN STATIONS

One direction instrumentation may take is in the development of anchored apparatus designed to measure at many depths at least the scalar quantities now used to describe the ocean water masses and their motions. An extended pattern of such stations outfitted to measure the ordinary scalars at several depths, on a schedule consistent with their spacing, would do much to indicate how steady or unsteady is the distribution of these properties of the ocean and the motions associated with them. The stations might be distributed in such a way that approximately equal volumes of water would pass between them. Were it convenient to measure the velocity of water passing these stations at several depths, the departures from geostrophic equilibrium might be detected as well as readjustments of the pressure pattern.

The stations might be equipped either to record or telemeter observations, or both. At first they might only make measurements of the temperature at a number of levels, and of the pressure at a few levels. This simple combination would permit studies of the fluctuation of the level of the thermocline and to some extent, the shifting boundaries of water masses having sufficient temperature contrast. Pressure indicators would indicate how much the wire is inclined, and this would suggest the presence of strong currents, supply information on their thickness and indicate the changing pattern of meanders. A light intensity meter in the surface float might serve the dual purpose of marking the lapse of days and estimating the cloudiness. It would also indicate the periods when the surface float had been towed under. Later on, some means for measuring salinity or density in situ would be desirable. Since these quantities are approximately known or can be found at each predetermined level, differential methods might be devised which use an enclosed water sample from that depth as a standard.

It is easier in several respects to develop or adapt existing instruments for such stations than to provide good ideas for a solution of the permanent anchoring problem. Stommel has calculated that a vertical steel wire of any diameter will not support its own weight with a safety factor of 2 if it is more than 30,000 feet long. Therefore, tapered wire seems desirable if steel is used. There is also the possibility of using materials other than steel which have sufficiently low density for buoyant forces to be important. The properties of a number of materials such as glass, various plastics, and non-ferrous metals have been reviewed. As yet no substance has been found free of certain disadvantages but the buoyant cable principle offers promise. If measurements are to be made at many levels the cable must contain electrical conductors although these need not be very heavy gauge. Various types of anchors have been considered. An ordinary coring tube driven into the bottom seems to have many good properties, and if the chain permitting the final free fall were quite long it would have a desirable shock-absorbing effect against sudden strains transmitted along the cable.

There is also a choice to be made as to whether the float at the upper end of the cable should ride on the surface or be held at a certain depth below it. A float at the surface would be subjected to violent wave action at certain times while a submerged float would be more protected. However, the stretching of cables several miles long may be considerable, and even if a float were initially below the surface, elastic extension and subsequent slow creep might allow it to reach the surface with effectively no scope. Either surfaced or submerged, buoys must be designed to withstand considerable hydrostatic pressure since they are liable to be towed under when they happen to lie in the paths of strong currents. It seems likely that buoys might be towed under to depths as great as 55 meters in the Gulf Stream, so that they must be designed to survive exposure to more than the pressure at this depth, even though they are to be primarily surface or near-surface floats.

There are advantages in placing buoys in the region of strong wave action since they may be recovered more easily and in this position they might provide information on the intensity of wave action or use it as a source of power. For example, a pendulum arranged to wind a spring could drive a generator as a trickle charger for storage batteries. It is interesting to note that storage batteries preclude the use of sealed floats due to the hydrogen they generate. A check valve of some kind will be required to prevent explosions.

Finally, there are the problems of telemetering or recording the data obtained at the stations and servicing the buoys. If the surface buoys are located far enough apart, the time of sunrise and sunset will schedule transmissions mainly according to longitude. Should a buoy break loose this fact will be known by the unusual transmissions schedule and the inconsistent nature of the data transmitted. If the buoy is not heard from for a few days it may have been towed under temporarily, but if it is not heard from for some longer time, it must be either sunk or in need of repair. Under these circumstances a service vessel is to be dispatched.

The service vessel will be faced with a difficult problem in navigation; to find an object nearly awash and possibly no more than 5 or 10 feet in diameter at anchor in 2 or 3 miles of water on a scope of perhaps 1.5 to 1. Sonar may help, but a radio homing transponder might shorten an otherwise lengthy search if the buoy has sunk. Since a service vessel may be needed quite often, it will have opportunities to contribute numbers of observations gathered en route.

Protest might be raised against ocean buoys as a menace to navigation. As a safety measure the buoys, though able to withstand fairly high hydrostatic pressure, should be brittle and break apart on impact. Glass and some plastics have this combination of properties. Similarly, the cable anchoring them to the bottom should be strong in tension but weak in shear, as are glass and some plastic fibers, so that the diving planes and screws of submarines may not be fouled. Plans have been considered in which a submerged float, to lift the burden of the cable's weight, lies below wave action, while a smaller float on the surface may house a radio transmitter and support the antenna. Buoys for this arrangement might be made to resist impact since the smaller float would have little inertia and its cable be small, while the deeper float and stronger cable might be placed below the range of submarine navigation.

From a more positive point of view, an extensive grid of anchored buoys, if listed on charts, might serve as position markers in the otherwise trackless ocean. If buoys were to be equipped with a suitable button marked "DISTRESS CALL" they might be activated to that purpose and serve as a mooring for lifeboats until help arrived. Such a service built into ocean buoys might cause them to be respected by mariners.

There has been some thought given to the choice of recording or telemetering data from ocean stations. It seems best that both be done. A telemetering installation will reveal whether or not the station is operating satisfactorily as well as provide a running account of the occurrences at its position. Such information would help in planning cruises as well as improve their effectivness while in progress. But since buoys may not always remain on the surface or transmitters may fail, the telemeter link may be broken from time to time. Records made within the buoy would help to fill the gaps in the telemetered record and provide a running check on the accuracy or origin of the information received by radio.

Recording apparatus for observations over an extended time is in process of development. Stommel and Frantz are considering designs for a recording buoy which will sink to the bottom and record the pressure. If the bottom pressure fluctuates tidally and level isobaric surfaces lie above the bottom, something may be learned of the ocean tides and the pressure fields associated with the deep circulation from such bottom mounted instruments. If the pressure fields associated with the motions above the thermocline are not in geostrophic equilibrium, the secular change in these may be recorded as well. Stommel has considered the problem of recovering these objects and believes that if a sufficient length of submarine cable is attached to each instrument, it should be possible to grapple for the cable, following the successful precedents of commercial cable companies. The results of recent experiments in shoal water are encouraging.

Other unattended recording instruments are actually in existence; namely the recording thermograph and the recording current meter designed by Klebba. These instruments cannot be set out at great depths as they are built at present, but they will record events for 400 days.

## DRIFTING BUOYS

In connection with present observational techniques, one of the most pressing interpretative problems is that of joining with pencil lines the scalar and vector observations made on successive traverses by one or more ships. Contours may be drawn through a field of scalars in several equally acceptable ways. Choices are more limited for a vector field and no choice can be justified without reference to at least a few representative streamlines or particle trajectories. There are also purely navigational difficulties of knowing where each observation was made in the geographic framework and since it takes time for ships to move about through the changing fluid structure, purely geographic considerations may not suffice. Usually we have no assurance that the changes in the fluid system are slow enough to be neglected in connecting the observations made at different times. The results of the multiple ship survey of the Gulf Stream in 1950 suggest that data from six ships could be safely collected for each day and treated as though they had all been taken simultaneously. The element of convenience doubtless weighed heavily in coming to this conclusion. From this, one is led to think that had it been posible to have not only moving ships in the field but drifting ships as well, the paths of motion and observations made by the ships drifting with the flow would have been useful guides in connecting observed points between the traverses made by the ships moving across the grain of the fluid structure.

Rather than drifting ships, it is, of course, more economical to use drifting buoys equipped to detect the local temperature and position and either to record these against time or telemeter the data to the ships or to shore. The streamlines described by drift of the buoys suggest a proper mode of interpolation between observations made on adjacent traverses by nearby ships. As each wave of buoys drifts through the same area, changes in the pattern of motions may be revealed. This kind of evidence is essential to a description of the fine structure of the transient state. In addition to evidence of the change in the strength of currents, horizontal confluence and difluence of surface flow, there may be a measurable change in the properties of the water parcel near each buoy as it moves through the area.

The drift of the buoys would only suggest the nature of the mean streamflow, for each buoy would tend to move in a random way with respect to the mean motion vector. Since the mechanism of eddy diffusion, particularly on a large scale, is not well understood, this might be studied separately by releasing a group of buoys at one point for the purpose of observing their scatter and the changes in water properties detected within the buoy field. It is also possible that in some regions where the current pattern is not immediately evident, the mean motion vector is small compared with the random component. Were the mean motion vector subtracted and the currents plotted, in effect, with respect to a reference frame moving at the mean motion rate, some intelligible systematic motions might appear.

In view of these possible uses for surface buoys and their apparent promise of new and desirable kinds of data not easily obtained from shipboard, some thought has also been given their use in obtaining subsurface data and the modifications of design that may be required.

Buoys which telemeter their position may be used, for example, to indicate currents and trends of motion at depths below the surface if they are equipped with large current crosses or other suitable drags to dominate their motions. With such equipment already below the surface it would be a relatively simple matter to suspend the drag on an electric cable and measure temperature or other scalars at that or lesser depths. It is also possible to suspend one or more current meters below an otherwise undamped surface buoy to measure the vertical shear. With the development of suitable inclinometers, a current cross might be used to measure vertical shear adapting the technique of Pritchard and Burt (1951).

The problem of position detecting systems for drifting buoys has a number of solutions the simplest of which, theoretically, is to relay loran signals as they are received at the buoy to a manned station where they can be compared and plotted. But loran and other pulsed radio transmissions require large bandwidths and the present areas of ground wave loran service are not very extensive. There are several phase difference methods for fixing and ranging on buoys which may be used more freely and can be operated anywhere at sea on an interrogation basis from a ship or shore point within the limits of ground wave transmission. If it ever becomes a routine matter to anchor buoys in the deep ocean, these might provide an independent reference system for either temporary hyperbolic navigation or ranging on buoys adrift. Outside the loran service areas this type of system would permit ships of buoys to work with continuous knowledge of the relative position of all points of observations, although the position with respect to the geographic coordinate system may be known with less accuracy.

In considering any such radio-location system, there is much to be gained if the ship is free to move through the buoy field making observations of other kinds. An anchored buoy reference system offers this possibility. If, however, the ship is sailed on a regular gridwork of courses, advancing with the buoys, it is possible for the position and rate of drift of the buoys to be discerned from the ship itself as the reference station. Ranges and bearings on each of a group of buoys may be repeated at intervals and if the ship has sailed along a straight course meanwhile, the ship's track provides a baseline for triangulation and ranging. These possibilities are being looked into at Woods Hole.

Beyond the problems of design of any radio telemetering system is the purely administrative problem of obtaining a suitable radio frequency allocation. According to present views, this should lie in the 1 to 3 megacycle range to provide some overlap of groundwave and skywave transmissions. Thus if a buoy drifts out of the groundwave reception area it may still be heard on skywaves. It seems improbable that pulsed signals would be permitted in this crowded range of radio frequencies because of the bandwidth requirements. Certain channels may be available, however, for continuous wave transmissions at low power. As radio telemetering systems are envisioned at the moment, the fraction of time on the air would be small but since the transmitters in the buoys would be unattended and scheduled either automatically or by interrogation from a ship, provision should be made for shutting them down in case of failure of the transmitter scheduling system. With the increasing use of aircraft in support of oceanographic ships, receivers aloft may prove useful if ranges become extreme or frequency allocations prove to be too high for successful surface reception.

Since such drifting apparatus is but an amplification of the ordinary current pole or current cross, and an ocean station is equivalent to an anchored ship, nothing very new is being tried. Yet, by adding radio to these otherwise time-honored methods, we may shift our point of observation almost at will.

# APPENDIX: CURRENT MEASUREMENT*

## WIND-DRIVEN SURFACE CURRENTS

To study the transfer of momentum between the air and the sea it seems necessary to be prepared to investigate both very large and very small scale phenomena. Apparatus for small scale studies of motion or the gradients of motions, temperature, and other properties through the sea surface and in waves are, to my knowledge, entirely lacking. However, some existing equipment may be useful in connection with studies of the larger scale surface motions and the vertical shear in the water phase. These are a pitot-type current meter recently devised by Willem Malkus, the current cross as used by Pritchard and Burt, and the G.E.K.

The Malkus bathypitotmeter (1953) has the form of a large bathythermograph and responds to currents in the range 50 to 250 cm/sec. It is necessary to move the ship ahead slowly if the current speeds do not fall in this range and then allow the instrument to come to equilibrium at each of a succession of depths to obtain readings. Readings on two headings must be made and composed to evaluate the resultant velocity at each level if this is not known at the start or if the current turns with depth. As far as I know there is no corresponding instrument for measuring the wind shear immediately above the sea surface although stereophotographs of vertical smoke trails have been considered.

Pritchard and Burt (1951) have found that for Reynolds numbers above 1000 the drag coefficient of a suitably weighted current cross remains constant over a usefully wide range of velocities, hence the angle of a wire supporting it is a simple function of the speed of the passing water. This convenient property of so familiar a device may have many applications as, for example, measurement of the vertical shear from a fixed or drifting station. If a recording inclinometer can be devised to accompany the current cross on its descent, it should be possible to measure vertical shear through great depths as well as small ones. Edmond Watson has constructed a device for measuring wire angle as a function of depth. This consists of a smoked glass slide moved in one direction by the action of pressure on a sylphon and a pendulum carrying a stylus to write the record of depth and incliniation. The pendulum is damped by the water which floods the instrument case. This might be adapted to cover a number of ranges of depth and might also house a recording thermograph so that the current shear and thermal gradients may be compared. Means for recording direction at great depths remain to be considered.

---

* - Mr. von Arx has suggested that his remarks made in the course of the discussions following his paper be presented in these proceedings as an appendix to the main body of the paper.

Current velocity measurements by the G.E.K. (von Arx, 1950a) suffer in magnitude when the current system extends downward through more than a negligible fraction of the total depth of water (Stommel, 1948). This may be a useful limitation in connection with studies of the wind-induced surface currents generated in the open sea by passing storms since Stern (Malkus and Stern, 1952) has shown that the signal due to local accelerations of the surface circulation by the wind is added directly to those produced by steadier geostrophic circulation at greater depths. Thus, if the background level at any station could be established in a period of calms, the accelerations of the surface layers due to wind at this place may be observed. A preliminary trial of this idea has been made from one weather ship on station and Bowden (1953) in England.

Another possibility in which the limitations of the G.E.K. can be turned to good use has been pointed out from theoretical considerations by Malkus and Stern (1952) who have reinvestigated the nature of the electric potential fields associated with motion of the water of the deep sea, taking account of both the horizontal and vertical components of magnetic flux.

According to the results of this study, the difference between the integrated surface current detected by the lateral drift of a ship and the integrated lateral component of current observed by G.E.K. is equal to the mean velocity of water beneath the line of traverse. From this and a knowledge of the average depth of water under the traverse, the volume transport may be computed. In mid-latitudes and in the vicinity of the strong western-ocean currents the differences may be large enough to be measured with useful precision with existing navigational and G.E.K. equipment. If means can be developed to make precise the necessary measurements of small differences between large quantities, this technique may be a valuable one since it provides a means for making observations of the mean velocity and of the volume transport independently of the geostrophic assumption.

## DEEP CURRENTS

Currents in the very deep parts of the oceans present special problems of measurement, not so much due to their inaccessibility but to their very small speed. If Kulp's figure of 1,750 years is a representative time during which this deep water may remain submerged, it then seems less likely that the circulation can be actively affected by the surface circulation through other than indirect processes. For example, if the thermocline rises and falls slowly in response to prolonged changes in the average wind stress, its variation in depth may be due either to a change in the overburden of light surface water, or the mechanism may be more directly related to the downward turbulent flux of heat. In the first case the thermocline might act as a diaphragm which shifts by displacement the very deep water masses below, while in the second case the thermocline would move but the water would not. If the first possibility is correct, and the sea level is not changed, a deepening of the level of the thermocline below the center of a light mid-ocean water mass due to increased average wind stress would be compensated by shoaling the level of the thermocline around its perimeter. The reverse effect might be expected if the average winds diminished. Such compensating motions of the thermocline would be peculiar to the diaphragm effect and thus distinguish it from the heat flux mechanism. Were the vertical motions or packing of iostherms in the thermocline to be studied synoptically by means of a grid of anchored buoys, such as those described earlier, the nature of some of the deep motions of the sea might be suggested. Still, direct measurements of the small motions at great depth would always be desirable.

## GEOLOGIC PROBLEMS

Marine geological processes have direct bearing on some types of currents as well as being affected in turn by the current systems. Since the recent visit of Professor Philip Keunen to the United States, there has been more general interest in his turbidity current hypothesis published more than a decade ago (Geol. Mag., 1938). The geologic record in cores and in marine deposits exposed on land contains examples of vertically and horizontally graded coarse materials deposited conformally on fine materials. In many cases these can be explained as load deposited far from land by turbidity currents. It would be of great interest to measure a turbidity current and then to sample the deposits it has produced.

It has been suggested that a number of buoyant spheres be anchored at intervals along the foot of the continental slope so that if a turbidity current were to pass one or more of these they would break loose and float to the surface. If found on shore, the floats would call attention to a suitable area for bottom sampling and coring.

More immediate information might be gained from one or a succession of electrical cables laid parallel to the foot of the continental slope at intervals of perhaps 100 kilometers seaward. A turbidity current cutting each of these cables in turn would give a succession of signals indicating its speed of advance and an estimate of the distance run. If the cable were moved but not parted, a measurable voltage would be developed which is proportional in magnitude to the speed and in its sense to the direction of the cable's motion through the magnetic field of the earth. One long cable would indicate when a turbidity current passed but would not indicate what part of its length had become involved. Shorter cable loops would localize occurrences better. While not ideally placed, there are already a number of commercial cables across the ocean floor. The full force of motional potentials derived from the displacement of a cable in a turbidity current would either mask or disrupt telegraph service. Commerical cable companies may have records available for research or might offer opportunities for more suitable recording of the signals now regularly received.

In studies of more localized geological processes controlled by currents, movable-bed hydraulic models may serve to clarify problems of sediment transport by longshore currents and the sorting of the coarser materials over the bottom. This particular use of models would require development. Engineering use of movable-bed models is traditionally concerned with the topography of the bottom rather than the structure of sedimentary deposits produced by moving water.

## ESTUARINE CIRCULATION

Studies of currents in coastal and estuarine areas is one of the traditional concerns of oceanographers. Despite the time that has been spent on the subject, very little significant progress has been made in methods for measuring of these complex current systems. The complexity of the circulation arises from the fact that there are many strong influences at work simultaneously. Broadly, these influences may be grouped as hydrologic, meteorologic, and oceanographic in nature. These groups of active forces work in confined situations so that for every parcel of water set in motion there may be simultaneously or eventually a corresponding parcel moving in reaction. The nature of the reactive motions depends to a large extent on the submarine topography of the region. The interplay of the active and reactive forces generally produces very complex circulation systems which may vary significantly from place to place and time to time within the same system. Therefore, estuarine circulations must either be studied in great detail or studied statistically.

Within the past few years progress has been made in a statistical approach to the problem of the flushing rate. Flushing, the progress of river water through an estuary, has been assumed to be indicated by the average distribution of salinity between the river mouth and the open sea. The recent theories of estuarine flushing by Ketchum (1951), Arons and Stommel (1951), Stommel and Farmer (1952), and others have been based on observations in widely different field situations such as the fjord type estuary (Tully, 1949), the coastal plane estuary (Pritchard, 1950, 1952) and the regions of the continental shelf in which the circulation is estuarine in character (Ketchum and others, 1951). The fact that this wide variety of systems yields a study from very nearly a single point of view is significant. It suggests that while the circulation systems may be quite different, the salinity distribution is achieved in much the same way in each case.

This has been explained through consideration of the combined tidal and wind-driven circulations as only a means by which the river and sea water masses are mixed within the estuary. River water tends to float stably on the salt water from the sea. As the river water moves down the estuary it becomes more saline due to salt from the sea water mixing upward from below. The net flow through the mouth of the estuary is seaward and equal to the river discharge. But since both the horizontal and vertical salinity gradients in the estuary tend to establish a more or less steady configuration, and salt is being carried out with the river water, there is a corresponding inward flux of salt water from the sea. The volumes of water exchanged to maintain the salt balance in an estuary may far exceed the river discharge during corresponding periods of time. This important mechanism seems to be present in estuaries of all kinds, though it may be obscured by the stronger action of tides, winds, branches of the offshore circulation and other effects.

A description of the manner in which mixing actually occurs and the paths followed by various parcels of water within an estuary is difficult to give fully, and is usually treated as a number of separate processes acting together. The importance of the several processes depends on the climate, the geometry of the wetted basin and the relief of the surrounding land, the tidal signature, river flow, permeability of the ground and other factors. For example, the circulation in fjord type estuaries which are deep, sheltered from the wind and often cut in hard impermeable rocks differs from the coastal plane estuaries which are generally broad and shallow, relatively unprotected from the wind, and often surrounded by soft and permeable sedimentary rocks. In fjords, wind and waves are less likely to be important influences on mixing, but the regular march of tides and changes of river discharge may control the circulation. In the coastal plane estuaries, wind, waves and tides may dominate the water motions and obscure the effects of river flow. In regions of the continental shelf where estuarine conditions exist, mixing may be strongly influenced by branches of the deep water circulation. It may be helpful to describe a few of these separate effects in turn. The current systems and mixing processes due to tidal action are often most conspicuous.

The tidal signature at the mouth of an estuary is but the beginning of what may be a complex sequence of wave motions within the embayment. Depending on the depth of water and the regularity of the boundaries, the wave may enter and travel as a single progressive wave slowly losing energy until it is damped completely, or it may be reflected back on itself. If the estuary is narrow and long the primary reflected waves are subject to analysis by the method developed by Redfield (1950). If the estuary is broad or dendritic, pairs of interfering waves may develop which set up a complex pattern of standing, progressive and rotary waves on the free surface. Since tidal currents flow in response to both the changing elevation of the free surface and the momentum acquired during their earlier history, the current may not be in phase with the wave form. To study this relationship, it is helpful to establish tide gauge stations around the perimeter of the estuary as well as to make current measurements.

In some instances the tidal currents are small and easily obscured by currents due to other causes. In such cases an intelligible synthesis of the tidal system can be gained through use of Froude models.

In other instances the tidal currents dominate the current system to the extent that the effects of river discharge, wind currents and so on, are obscure. Since the river discharge pattern is important in a consideration of the flushing rate, and the tidal motions may ebb strongly where the salinity is low and flood strongly at another place to maintain the salt balance in the estuary, it is useful to measure simultaneously the tidal volume inequality and the salinity. The observational requirements are stringent since the volumes of flow may be large and the differences small.

As though it were not enough that tides are reflected and progress in different phase than associated currents, the tidal signatures may be unsymmetrical and change progressively from day to day with the changing configuration of the astronomical bodies causing them. Semi-diurnal tides occur along most mid-latitude coasts but there are regions such as the Gulf of Mexico where diurnal tides predominate and then give way to semi-diurnal tides twice each month. Since this tidal sequence may produce a more or less complete reorganization of the tidal wave and current pattern every two weeks, rapid survey techniques are required and data for statistical treatment are best taken over at least a synodic period. Again the Froude model has served to show how the tidal circulation changes with the passage of time.

In shallow, narrow channels or estuaries through which the river discharge is large, sea water may enter as a flat wedge moving under the lighter mixed water containing the river discharge. A salt wedge intrusion influences the vertical structure of currents. Over the course of a symmetrical tidal cycle, the net flow in the salt wedge should be landward in order to carry the salt required to increase the salinity of the predominantly seaward motions of the river discharge. Since there may be a difference in temperature as well as salinity at the interface between the salt wedge and the river discharge, the position of direct current measurement stations with respect to a salt wedge may be chosen in the light of the distribution of temperature or salinity.

The consequences of the existence of a salt wedge to both the circulation and mixing of salt and fresh water have been studied intensively in recent years by Keulegan (reprinted, 1950) and by Farmer (1951) in idealized models. The staff of the Mississippi Waterways Experiment Station, Engineering Department of the University of California at Berkeley, and other laboratories, have made much longer series of observations both in the field and in models of field situations. The latter studies have been made primarily for engineering purposes, but have provided basic data that have proved valuable for tests of the statistical theories of flushing and investigations of the behavior of the salt wedge.

The jet (von Arx, 1948) is another form of intrusion that may be important in some well enclosed estuaries where wind mixing is significant, or the river discharge small. Jet flow may occur through narrow passages when the water in the estuary is mixed to the extent that the isohaline surfaces are nearly vertical and the water density at the entrance is equal to that of the sea. In this circumstance there is no stable mode of intrusion, such as the salt wedge, by which sea water may enter with the flood tide; hence the inward flow tends to be equally rapid at all levels except for the effects of bottom or side friction. In this case, too, the average ebb volume should exceed the average flood volumes by the river and ground water discharge.

Under the conditions of complete vertical mixing that favor jet flow there are opportunities for simple overturning motions to develop under wind stress. The wind-driven circulation tends to overturn in the manner somewhat like a belt on two pulleys turning on axles at right angles to the wind. In such simple systems the surface layer moves with the wind at a more or less steady speed but increases in thickness with fetch. Generally, the surface layer occupies less than half the total depth so that the upwind return current moving over the bottom is slower.

In a stratified estuary the wind-driven motions may be layered. The surface layer may have an overturning circulation of its own moving downwind on the surface and upwind along an interface which rises upwind. The frictional stress on the interface may cause the bottom layer to develop a circulation overturning in the reverse sense. It is possible that the interface may be so steeply inclined that the heavier stratum of water reaches the free surface at the upwind end of the embayment. In this case the circulation of bottom water may overturn in the same sense as the surface layer provided the circulation due to wind stress is stronger. The wind-driven and frictional driven parts of the bottom circulation may also occur as two independent cells, in which case the line along which the density interface cuts the free surface will also be a line of horizontal convergence below which water sinks.

If the wind stress produces waves with an amplitude equal to a major fraction of the total depth of water, all traces of stratification may disappear. This occurs in shallow water, sometimes to the extent that bottom sediments are caught up in the wave action. Due to the strong vertical transfer of momentum, the overturning wind-driven circulation may actually slow down even though the free surface is strongly inclined. Studies of the setup under very strong winds have been made by Haurwitz (1951), Saville (1952), and under laboratory conditions by Keulegan (1951).

A study of the wind-driven circulation of the Scotian shelf has been made recently by Longard and Banks (1952) and suggests the effect of wind on deeper, less confined water along a relatively straight coastline. Due to the fact that the circulation was less influenced by the land, the wind-induced slope of the density interfaces gave rise to longshore currents and a helical circulation in the surface layer.

Current measurements in estuaries are usually made directly although dynamic sections are also made particularly in connection with chemical investigations. Some of the instruments available for direct current measurements in estuaries and coastal waters are listed by Adams (1942), Sverdrup and others (1942), Romanovsky (1949) and von Arx (1950b). A critique of the ideal current meter has been given by O'Brien and Folsom (1948). A valuable discussion of the the use of the current pole in tidal waters has been written by Haight (1938). There is, however, a great variety of methods: sonic methods, strain gauge, capacitance and transducer methods, electromagnetic methods, dye tracers, ionization tracers, radioactive tracers, wire angle techniques, and others, which differ completely from the mechanical current meter methods that ordinarily come to mind. Many of the thermal and electrical methods were conceived to study very rapid changes in turbulent flow on a small scale. Since oceanographic observations are more generally concerned with large scale processes, clumsier methods may be more suitable. For example, the broad features of the bottom circulation in clear, shoal water can often be discerned from a study of the "sediment shadows" behind obstacles in the paths of the swiftest currents. These are often most clearly shown on aerial photographs of the estuary. Dye marker or mimeograph paper dropped from aircraft can be photographed to measure the surface currents. This technique permits large areas to be surveyed in a few hours and is especially valuable when wind stress constitutes an important driving force. It has been found that current measurements can be made with dye dropped from heavy aircraft in weather that is too boisterous for current measurements to be made successfully from anchored ships. Fluorescein dye charges must be increased when the light is poor or when the water is turbid. If fluorescein does not show plainly enough to be photographed, mimeograph paper can be used. .Mimeograph paper has the property of soaking rapidly without curling and will usually drift just under the surface. It is not capable, however, of being anchored to produce streamers and reference points in the photographs, as is fluorescein in cloth bags. In clear water on bright days it is possible to drop a weighted charge of fluorescein through the water column and in that way study the change or velocity with depth. Stereoscopic pairs of photographs can be made and if the depth of water is known the significant current velocity changes can be measured at several levels.

Models have also been used in connection with oceanographic studies of estuaries and coastal circulations. Tully (1949) and Barnes and Lincoln ( in preparation) have built models of fjord type estuaries for which they found Reynolds scaling most suitable. For coastal plain estuaries, Froude scaling has been used with adjustment of the density ratio of the mixing sea and river water components by approximately the reciprocal of the vertical exaggeration (von Arx, 1950c). Models serve to guide field work in that they reveal the manner in which observations made at several points are related and often suggest where more critical observations are needed or may best be made. Aside from the field program, however, models may also serve to reveal the contribution to the whole complex circulation pattern made by each of the principle groups of forces. The effect of tides may be isolated as may be the effects of river discharge, wind force and direction, and the offshore circulation. Combinations of these may be produced experimentally to study the circumstances which produce particularly favorable or unfavorable ecological conditions or influence the flushing rates in certain restricted areas where sewage, industrial wastes or other contaminants may be pocketed.

It is interesting to note that while very great advances have been made in recent years providing statistical means for calculating the flushing rate of estuaries and the dispersal of contaminants in coastal waters, there have been no great improvements in methods for studying the circulation itself. Thus, even in relatively small scale problems of oceanography, it is difficult to reconcile the broad or statistical properties of the circulation with its active mechanisms.

## DISCUSSION: Columbus O'D. Iselin

In the study of North Atlantic circulation we are finding that the law of diminishing returns has begun to set in, so far as conventional observations are concerned. A few thousand more deep temperature and salinity stations are not likely to provide much additional understanding, unless supplementary, new types of data are secured simultaneously. Thus at Woods Hole we feel that buoys hold considerable promise of filling some of our pressing needs and that their development should be pursued as vigorously as available funds permit.

The great advantage of a buoy is that it can secure a continuous record over a considerable period of time. The longer the life of the buoy, in most applications, the greater will be the returns. This means that the buoy must continue to function during periods of stormy weather. Either the buoy case must be rather large or it must be submerged below the depth of effective wave action.

Surface buoys are attractive in that they can store or transmit both meteorological and oceanographic observations. What is the optimum shape for such a buoy and how large must it be in order to ride out a gale? On the continental shelf the experience with navigation buoys is more or less applicable, but only cable ships occasionally set buoys in deep water and then for only rather short periods of time. It seems likely that a successful surface buoy must displace at least a ton. It should probably be shaped like a hydrometer and would therefore have very considerable vertical dimensions. The weakness of such a design may be that in strong winds too often a moored buoy will tow under. The very data that such a buoy could secure is needed before a convincing design study could be made. Much the same is true of the mooring problem. We can only guess at the depth and velocity of the transitory currents that the buoy will experience.

For these reasons it seems only prudent to approach the open ocean buoy problem rather cautiously, although it is in deep water that the greatest scientific returns can be expected. Experience with unmoored buoys and with buoys anchored on the continental shelf will probably indicate the most desirable characteristics of a combined meteorological and oceanographic buoy for deep water. If such a buoy could supplement or substitute for weather ships a very considerable engineering effort would be justified. By experimenting with smaller and more limited buoys oceanographers can perhaps show how feasible the more elaborate, all purpose, moored observational platform would be.

## DISCUSSION: Richard H. Fleming

I have been asked to comment on Mr. von Arx's paper, although circumstances made it impossible for me to attend the symposium. After long and hard thought about what I might say, I have decided that any suggestions or ideas that were sufficiently radical or provocative would undoubtedly start an argument and that in this case I should be present in person to defend myself. Having thus alibied myself, I would like to say that the possibility of employing self-recording or telemetering buoys has been on my mind for many years and in future developments in oceanography I am positive that such devices will be used to an ever-increasing extent. The manpower in oceanography is so limited that we must employ every means at our disposal to reduce the labor of data collection and, as Mr. von Arx has pointed out, buoys can be used in certain cases to greater advantage than ships. The one thing that always worries me in proposals of this kind is the cost in man-hours involved in the development, construction and use of such equipment. All of us must consider very carefully the relative importance of developing new equipment compared to the more effective use of existing devices.

There are three points that I would like to emphasize in connection with all problems of instrumentation. First, let us carefully consider the individual job at hand before undertaking to develop a new device. I feel that even with existing instruments many are either too accurate or too complicated for the jobs for which they are actually used. Second, simplicity of construction and operation must always be kept before us. Simplicity implies economy of materials and manpower and will reduce the caliber and number of personnel required for work at sea. Third, mechanical methods of data handling must be developed to reduce the amount of manual labor currently demanded by practically all types of oceanographic observing systems before the records are in usable form. This is an old story that I have told many times and will continue to repeat until the instrument designers are conscious of the problem and will engineer their systems so that the records are obtained in a readily usuable or mechanically analyzable form. There are two related aspects to this problem that must not be forgotten. These are, to provide analyzing equipment that is capable of handling data from a variety of instruments and of a wide variety of phenomena, and to improve methods for the storage and handling of such information.

We are living in an age of gadgets. By all means let us take advantage of their help but do not let them become our masters. Our knowledge of the oceans is so fragmentary that the main problem is often to decide what to measure, not how to measure it. Instruments cannot take the place of brains and can be of real assistance only when we tell them what to do. In the present stage of development of oceanography it is essential that there be full cooperation between the theoretical worker, the field investigator, the analyst and the instrument designer. If such coordination is developed and we maintain a proper distribution of effort between them, rapid progress will be assured.

DISCUSSION: D.W. Pritchard

Mr. von Arx has in a very excellent manner described some of the possible observational techniques for increasing our knowledge of oceanic circulation. The concept of utilizing anchored or drifting buoys for collecting synoptic data has been envisioned by a number of oceanographers, but von Arx has for the first time brought together in a single paper much of the present thinking on the subject.

My brief contribution here is to suggest that many of the techniques discussed by von Arx might be advantageously pursued first through inshore and estuarine studies. In the studies of deep oceanic circulation the problems of suitable sensing elements for the parameters to be measured, of suitable recording or transmitting equipment and of suspension and anchoring of the equipment, must all be solved before successful anchored buoy stations can be utilized. In the relatively shallow water of estuaries and inshore areas some of the problems become less acute and there is an opportunity to test component parts of equipment which may later serve for deep water studies -- and at the same time obtain valuable information concerning estuarine and inshore circulation.

Despite the fact that the studies of estuaries often involve relatively small areas compared to the open ocean, the need for recording buoys in order to obtain synoptic information remains about as acute as in the case of the open sea because the time scale of transient changes is much more rapid in the estuary as compared to the open sea. Thus, though there is less area to cover in the estuary as compared to the open sea, it must be covered in much less time in order to obtain reasonably synoptic data.

As a start toward obtaining recording buoy stations for shallow water studies, the Chesapeake Bay Institute is now completing the adaptation of the CTI into a five-depth buoy recorder for temperature and conductivity. At present the device is designed to record each half hour for a period of ten days at five depths between the surface and 150 feet. Also nearing completion is a current meter which will record the magnitude and direction of the water motion each half hour for a ten day period. This latter unit is designed especially for inshore studies where fouling of moving parts of the conventional current meters presents a problem. The CBI device has no moving parts, utilizing acoustical means to obtain the water velocity.

Dr. Fleming, in his comments on this subject, has warned against placing too much emphasis and effort on instrumentation as opposed to utilizing the facilities we now have to increase our fragmentary knowledge of the oceans. From my viewpoint the lack of suitable instruments remains one of the most critical factors in holding back our proper understanding of the physical phenomena occurring in the ocean and the inshore areas bordering the ocean. Almost every theoretical attempt to explain circulation or diffusion in the ocean or the inshore waters requires for ultimate proof or disproof observations which cannot be obtained with present facilities.

One last comment on desirable instrumentation for shallow water studies which may have general application in oceanography. Our knowledge of the spectrum of turbulent motion in the ocean is almost completely lacking. The possibility of observing this spectrum in the open sea appears somewhat remote, since suitably securing the sensing elements would be almost impossible. Some information might be obtained in shallow water through the use of towers secured to the bottom, much as the turbulence in the lower layers of the atmosphere is studied. The tower, with suitable sensing elements attached, could be constructed on a pontoon barge, which could then be towed to a suitable location, the pontoons flooded, and the assembly sunk into position. When the operation is completed, aqualung swimmers could be utilized to attach air hoses to the pontoons and the assembly could be refloated, to be used in another location. Measurements obtained from such an installation could be used to check the indirect determinations of the non-advective flux of momentum and salt in estuaries, and would be very valuable in the further development of flushing theories.

## REFERENCES: W.S.Von Arx

ADAMS, K.T. 1942 "Hydrographic Manual". *rev. ed. U.S.Coast and Geodetic Survey, Special Pub. No. 143. 940 pp.*

ARONS, ARNOLD, B., and STOMMEL, HENRY. 1951. "A Mixing-Length Theory of Tidal Flushing". *Trans. Am. Geophys. Un. Vol. 32, no. 3, pp. 419-421.*

BARNES, C.A., and LINCOLN, JOHN H. 1952. "An Hydraulic Model of the Puget Sound Area". *(In Preparation).*

**FARMER, HARLOW G.** 1951. "An Experimental Study of Salt Wedges". *Woods.Hole Oce. Inst. Tech. Rept. Ref. No. 51-99. 21 pp. with tables.*

FUGLISTER, FREDERICK C. 1951. "Annual Variations in Current Speeds in the Gulf Stream System". *Sears Found. J. Mar. Res. Vol. X, No. 1, pp. 119/127.* 1951b. "Some Fesults of a Multiple Ship Survey of the Gulf Stream". *Tellus. Vol. 3, No. 1, pp. 1-14.* 1951c. "Multiple Currents in the Gulf Stream System". *Tellus. Vol. 3, No. 4, pp. 230-233.*

HAIGHT, F.J. 1938. "Currents in Narragansett Bay, Buzzards Bay, and Nantucket and Vineyard Sounds". *U.S.Coast and Geodetic Survey, Spec. Pub. No. 208. 100 pp.*

HAURWITZ, B., and PANOFSKY, H.A. 1950. "Stability and Meandering of the Gulf Stream". *Trans. Am. Geophys. Un. Vol. 31, pp. 723-731.* 1951. "The Slope of Lake Surfaces Under Variable Wind Stresses". *U.S.Beach Erosion Board. Tech. Memo. No. 25. 23 pp.*

ISELIN, C. O'D. 1940. "Preliminary Report on the Long-Period Variations in the Transport of the Guld Stream System". *Papers Phys. Oceanog. and Meteral. Vol. VIII, No. 1, pp. 1-40.*

ISELIN, C. O'D., and FUGLISTER, FREDERICK C. 1948. "Some Recent Developments in the Study of the Gulf Stream". *Sears Found. J. Mar. Res. Vol. VII, pp. 317-329.*

KETCHUM, BOSTWICK H. 1951. "The Exchanges of Fresh and Salt Waters in Tidal Estuaries". *Sears Found. Journ. Mar. Res. Vol. X, No. 1, pp. 18-38.*

KETCHUM, B.H., REDFIELD, ALFRED C., and AYERS, JOHN C. 1951. "The Oceanography of the New York Bight". *Papers Phys. Oceanog. and Meterel. Vol. XII, No. 1, pp. 1-46. Mass. Inst. of Tech, Words Hall Oceanog. Inst. Contrib. 549.*

KEULEGAN, G. 1950. "Model Laws for Density Currents".*(reprinted). Proc. Colloquim on the Flushing of Estuaries, Sept. 7-8, Mass. Inst. Tech. pp. 65-126.*

KEULEGAN, G.H. 1951. "Wind Set-Up in Small Closed Channels". *J. Res. Nat. Bur. Stand. Vol. 46, No. 5, pp. 358-381.*

LONGARD, J.R., and BANKS, R.E. 1952. "Wind-Induced Vertical Movement of the Water on an Open Coast". *Trans. Am. Geophys. Un. Vol. 33, No. 3, pp. 377-380*

MALKUS, WILLEM V.R., and STERN, MELVIN E. 1952. "Determination of Ocean Transports and Velocities by Electromagnetic Effects". *Sears Found. J. Mar. Res. Vol. XI, NO. 2, pp. 97-105.*

## REFERENCES: W.S. Von Arx Cont'd.

MUNK, WALTER, H. 1947. "A Critical Wind Speed for Air-Sea Boundary Processes". *Sears Found. J. Mar. Res. Vol. VI, No. 3, pp. 203-218.* 1950. "On the Wind-Driven Ocean Circulation". *J. Met. Vol. 7, No. 2, pp. 79-93.*

O'BRIEN, M.P., and FOLSOM, R.G. 1948. "Notes on the Design of Current Meters". *Trans. Am. Geophys. Un. Vol. 29, No. 2, pp. 243-250.*

PRITCHARD, D.W. 1950. "Notes on the Dynamics of Estuarine Waters". *Proc. of the Colloquium on the Flushing of Estuaries, Sept. 7-8, Mass. Inst. Tech. pp. 49-60.* 1952. "A Review of our Present Knowledge of the Dynamics and Flushing of Estuaries". *Chesapeake Bay Inst., Johns Hopkins Univ. Tech. Rept. IV. 45 pp.*

PRITCHARD, D.W., and BURT, WAYNE V. 1951. "An Inexpensive and Rapid Technique for Obtaining Current Profiles in Estuarine Waters". *Chesapeake Bay Inst., Johns Hopkins Univ. Tech. Rept. No. I. 16 pp.*

REDFIELD, ALFRED C. 1950. "The Analysis of Tidal Phenomena in Narrow Embayments". *Papers Phys. Oce. and Met. Vol XI, no. 4, pp. 1-36.*

ROMANOVSKY, M.V. 1949. "Les Mesures Directs des Courants Marins". *Annales Hydrographiques. No. 1357. pp. 2-34.*

SAVILLE, THORNDIKE, JR. 1952. "Wind Set-Up and Waves in Shallow Water". *U.S.Beach Erosion Board. Tech. Memo. No. 27. 36pp.*

STOMMEL, HENRY. 1948a. "The Westward Intensification of Wind-Driven Ocean Currents". *Trans. Am. Geophys. Un. Vol. 29, No. 2, pp. 202-206.* 1948b. "Theory of the Electric Field Induced in Deep Ocean Currents". *Sears Found. J. Mar. Res. Vol. VII, No. 3, pp. 386-392.*

STOMMEL, HENRY, and FARMER, HARLOW G. 1952. "Abrupt Change in Width in Two-Layer Open Channel Flow". *Sears Found. J. Mar. Res. Vol XI, no. 2, pp. 205-214.*

SVERDRUP, H.U., JOHNSON, MARTIN W., and FLEMING, RICHARD H. 1942. "The Oceans, Their Physics, Chemistry and General Biology". *Prentice-Hall, Inc., New York. 1087 pp.*

TULLY, J.P. 1949. "Oceanography and Prediction of Pulp Mill Pollution in Alberni Inlet". *Bull. Fish Res. Bd. Canada. Vol. 83, pp. 1-169.*

VON ARX, W.S. 1950a. "An Electromagnetic Method for Measuring the Velocities of Ocean Currents from a Ship Under Way". *Papers Phys. Oce. and Met. Vol. XI, No. 3, pp. 1-62.* 1950b. "Synoptic Models of the Circulation in Estuaries". *Proc. Colloquium on the Flushing of Estuaries, Sept. 7-8, Mass. Inst. Tech. pp. 24-42.* 1952a. "Preliminary Results of Some Oceanographic Experiments in a Rotating Basin". *Tellus (In press).* 1952b. "Notes on the Surface Velocity Profile and Horizontal Shear Across the Width of the Gulf Stream". *Tellus. Vol. 4, No. 3, pp. 211-214.*

YU, YI-YUAN, 1952. "Breaking of Waves by an Opposing Current". *Trans. Am. Geophys. Un. Vol. 33, No. 1, pp. 39-41.*

## REFERENCES: W.S.Von Arx Cont'd

FUGLISTER, FREDERICK C. 1951. "Annual Variations in Current Speeds in the Gulf Stream System". *Sears Found. J. Mar. Res. Vol. X, No. 1, pp. 119-127.*

FUGLISTER, FREDERICK C., and WORTHINGTON, L.V. 1951. "Some Results of a Multiple Ship Survey of the Gulf Stream". *Tellus. Vol. 3, No. 1, pp. 1-14.*

HAURWITZ, B., and PANOFSKY, H.A. 1950. "Stability and Meandering of the Gulf Stream". *Trans. Am. Geophys. Un. Vol. 31, No. 5, pp. 723-731.*

ISELIN, C.O'D. 1940. "Preliminary Report on the Long-Perion Variations in the Transport of the Gulf Stream System". *Papers Phys. Oceanogr. and Met. Mass. Inst. Tech. Vol. VIII, No. 1, pp. 1-40.*

ISELIN, C. O'D., FUGLISTER, FREDERICK C. 1948. "Some Recent Developments in the Study of the Gulf Stream". *Sears Found. J. Mar. Res. Vol. VII, No. 3, pp. 317-329.*

MUNK, WALTER H. 1950. "On the Wind-Driven Ocean Circulation". *J. Met. Vol. 7, No. 2, pp. 79-93.*

PRITCHARD, D.W., and BURT, WAYNE V. 1951. "An Inexpensive and Rapid Technique for Obtaining Current Profiles in Estuarine Waters". *Chesapeake Bay Inst., Johns Hopkins Univ. Tech. Rept. No. 1. 16 pp.*

STOMMEL, HENRY. 1948. "The Westward Intensification of Wind-Driven Ocean Currents". *Trans. Am. Geophys. Un. Vol. 29, No. 7, pp. 202-206.*

VON ARX, W.S. 1952a. "Notes on the Horizontal Shear and Surface Velocity Profile Across the Width of the Gulf Stream". *Tellus. Vol. 4, No. 3, pp. 211-214.* 1952b. "A Laboratory Study of the Wind-Driven Ocean Circulation". *Tellus. Vol. 4, No. 4, pp. 311-318.*

## REFERENCES: W.S. Von Arx's Appendix

ADAMS, K.T., 1942: "Hydrographic Manual". *USC&GS Spec. Pub. No. 143:940 pp.*

ARONS, ARNOLD B. and STOMMEL, HENRY, 1951: "A mixing-length theory of tidal flushing". *Trans. Amer. Geophys. Un., 32 (3): 419-421.*

BARNES, C.A. and LINCOLN, JOHN H. "An hydraulic model of the Puget Sound area". *(in preparation).*

BOWDEN, K.F., 1953: "Measurements of wind currents in the sea by the method of towed electrodes". *Nature, 171: 734-737.*

FARMER, HARLOW G., 1951: "An experimental study of salt wedges". *Woods Hole Oceanogr. Inst. Ref. No. 51-99 (unpublished manuscript).*

HAIGHT, F.J., 1938: "Currents in Narragansett Bay, Buzzards Bay, and Nantucket and Vineyard Sounds". *USC&GS Spec. Pub. No. 208: 100 pp.*

HAURWITZ, B., 1951: "The slope of lake surfaces under variable wind stresses" *Beach Erosion Bd. Tech. Memo. No. 25: 23 pp.*

KETCHUM, B.H., 1951: "The exchanges of fresh and salt waters in tidal estuaries". *J. Mar. Res., 10 (1): 18-38.*

KETCHUM, B.H., REDFIELD, A.C., and AYERS, J.C. 1951: "The oceanography of the New York bight". *Pap. Phys. Oceanogr. Meteorol., 12 (1): 1-46.*

KEULEGAN, G., 1950: (reprinted) "Model laws for density currents". *Proc. Colloquium on the flushing of eetuaries, M.I.T., Cambridge, Mass., Sept. 7-8, 1950: 65-167.*

KEULEGAN, G.H., 1951: "Wind set-up in small closed channels". *Journ. Mar. Res. Nat'l. Bur. Stds, 46 (5): 358-381.*

LONGARD, J.R., and BANKS, R.E. 1953: "Wind-induced vertical movement of the water on an open coast". *Trans. Amer. Geophys. Un., 33 (3): 377-380.*

MALKUS, WILLEM V.R., 1953: "A recording bathypitotmeter". *J. Mar. Res., 12, (1): 51-59.*

MALKUS, W.V.R., and STERN, M.E., 1952: "Determination of ocean transports and velocities by electromagnetic effects". *J. Mar. Res., 11 (2): 97-105.*

O'BRIEN, M.P., and FOLSOM, R.G. 1948: "Notes on the design of current meters". *Trans. Amer. Ceophys. Un., 29 (2): 243-250.*

PRITCHARD, D.W., 1950: "Notes on the dynamics of estuarine waters". *Proc. Colloquium on the flushing of estuaries, M.I.T., Cambridge, Mass., Sept. 7-8, 1950: 49-60.*

PRITCHARD, D.W., 1953: "A review of our present knowledge of the dynamics and flushing of estuaries". *Tech. Rept. IV, Chesapeake Bay Inst. of Johns Hopkins Univ.*

## REFERENCES: W.S.Von Arx's Appendix Cont'd.

PRITCHARD, D.W., and BURT, W.V. 1951: "An inexpensive and rapid technique for obtaining current profiles in estuarine waters". *J. Mar. Res., 10 (2): 180-189.*

REDFIELD, ALFRED C., "The analysis of tidal phenomena in narrow embayments". *Pap. Phys. Oceanogr. Meteorol., II (4): 36 pp.*

ROMANOVSKY, V., 1949: "Les mesures directes des courants marins". *Annales Hydrographiques, No. 1357: 34 pp.*

SAVILLE, THORNDIKE, JR., 1952: "Wind set-up and waves in shallow water". *Beach Erosion Bd. Tech. Memo. No. 27: 36 pp.*

STOMMEL, HENRY, 1948: "The theory of the electric field induced in deep ocean currents". *J. Mar. Res., 7, (3): 386-392.*

STOMMEL, HENRY, and FARMER, HARLOW G. 1952: "Abrupt change in width in two-layer open channel flow". *J. Mar. Res., II (2): 205-214.*

SVERDRUP, H.U., et al, 1942: "The Oceans". *Prentice-Hall, Inc., New York: 1087 pp.*

TULLY, J.P., 1949: "Oceanography and prediction of pulp mill pollution in Alberni Inlet . *Bull. Fish. Res. Bd. Canada, 83: 169 pp.*

VON ARX, W.S., 1948: "The circulation systems of Bikini and Rongelap lagoons" *Trans. Amer. Geophys. Un., 29 (6): 861-870.*

VON ARX, W.S., 1950a: "An electromagnetic method for measuring the velocities of ocean currents from a ship under way". *Pap. Phys. Oceanogr. Meteorol., 11 (3): 1-62.*

VON ARX, W.S., 1950b: "Some current meters designed for suspension from an anchored ship".*J. Mar. Res., 9, (2): 93-99.*

VON ARX, W.S., 1950c: "Synoptic models of the circulation in estuaries". *Proc. Colloquium on the flushing of estuaries, M.I.T., Cambridge, Mass, Sept. 7-8, 1950: 24-42*

# BIOLOGICAL INSTRUMENTS

Elbert H. Ahlstrom

## GENERAL

Of prime importance in the study of plants and animals in the sea are instruments designed for their collection. Whether we are interested in merely determining the kind of organisms present and their geographic and bathymetric distribution, or in the more complex problems of population dynamics as related to the physical, chemical and biological factors of the environment, we need gear that will provide representative samples of plants and animals.

Obtaining adequate samples of marine organisms is not a simple problem. This is equally true whether we are interested in determining the distribution and abundance of a single species, or in sampling a biological community such as the phytoplankton or the organisms making up the deep scattering layer. Even our best collecting gear can obtain only a small and often inadequate sampling of a population whose distribution may be both very widespread and irregular.

We are all aware of the diversity of plant and animal life in the sea: a range in size from bacteria to whales; a diversity of habitat from the shoreline to the benthic deeps, from the surface film through all levels of the oceanic province; a range in motility from sessile forms attached to the bottom or organisms passively carried by currents, to such powerful swimmers as whales and sharks. Of necessity, there must be a great variety of biological instruments, for locating, observing, collecting or culturing organisms so diverse in size, habitat and motility.

The biologists use a convenient classification of marine organisms based upon their ecological distribution and habits. They divide the population of the sea into three large groups - the benthos, nekton and plankton. Benthic organisms are found on the bottom of the sea. The nekton is composed of actively swimming animals such as fish, whales and squid that inhabit the pelagic zone. The plankton include plant and animal organisms, usually microscopic in size, that drift more or less passively with the currents. The floating plants, principally composed of diatoms and dinoflagellates, are collectively known as phytoplankton. The animal plankton, known as zooplankton, include not only a multitude of species that pass their whole life in a floating state, but also countless larvae and eggs of the animals composing the benthos and nekton. Much of biological instrumentation is concerned with the sampling of organisms in the one or the other of these large groups.

Recent advances in instrumentation in the biological field are neither as spectacular nor as novel as in some of the other fields which will be treated in this symposium. Most of our standard sampling gear is of venerable age. Except for gear used in commercial fishing, there has been no economic incentive to develop biological collecting gear. Unfortunately, biologists are not as mechanically inclined as many other scientists.

## PLANKTON SAMPLING EQUIPMENT

As I have been more directly concerned with the problems of plankton sampling, I will discuss first the new developments in this field.

In quantitative plankton research, considerable effort has been expended in finding reliable methods for collecting plankton samples from the sea, and in working up the material. Due to the limitations of any type of sampler employed in collecting plankton, as well as to the actual clumpiness of plankton distribution in the sea, no instrument will obtain a fully representative sample of the organisms present in the water. Most samplers are selective in one way or another. The selection may be a size selection, resulting from loss of organisms through the meshes of the net employed. The selection may be due to the avoidance of the sampler by the more agile planktonic organisms -- a motility -- influenced selection. The selection may result from mechanical limitations of the gear, from limitations in its operation, or from many other causes.

I wish to discuss three of the more outstanding instruments designed for the quantitative collection of plankton. These are by no means the only new plankton collecting devices that could be included.

Hardy Plankton Recorder - Although the Hardy plankton recorder is not a new instrument, it has not been used by workers in this country until recently. It was demonstrated at several institutions during the past year by K. M. Rae. This instrument has been used so continuously and effectively in research on the plankton of the North Sea and other areas, that it certainly ranks as one of the most important instruments for plankton sampling now in use.

The Hardy plankton recorder was used for the first time during the Discovery Expedition to the Antarctic in 1925-27, but it was not described in any detail until 1936. It was designed to take a continuous sample over distances as great as several hundred miles. It is ordinarily towed at a depth of about 10 meters at a vessel speed of 8 to 16 knots.

The front end of the recorder is provided with a small orifice (about $1\frac{1}{4}''$ square) which may be reduced, if desired, to $\frac{1}{2}''$ or less. The water, after entering the body of the recorder, is led through a wider tunnel, across which is stretched a band of silk or nylon gauze. The gauze band is slowly wound across the water tunnel and into a preservative chamber where it is spooled and stored in a bath of formalin. The spooling mechanism is geared to an external propeller which is turned by passing water, hence the spooling is in direct relation to the distance travelled. Because of this, it is possible to determine the approximate locality where each portion of the continuous plankton sample was obtained. To facilitate working with the material ashore, the straining band is graduated into numbered divisions.

The instruments have been made sufficiently fool-proof, so that they can be used on merchant vessels on routine runs between ports. Most of the sampling is done on such vessels. The sampling done in a year by these instruments now amounts to about 30,000 miles of plankton records, an impressive total. The use of the plankton information by the herring fishery in increasing its catch has become one of the classic examples of the practical value of planktonic research.

The Hardy plankton recorder gives a continuous line of ecological observation across an area being investigated. Patchiness in the distribution of plankton can be effectively investigated with this instrument. However, every method of plankton collection has its limitations, and the most serious disadvantages of this instrument are (1) it is designed for towing at a single depth only, and this near the surface, and (2) the organisms are crushed when rolled up in the filtering band, making identification difficult.

Clarke-Bumpus Sampler - Another plankton sampler that has received wide acceptance during the past few years is the Clarke-Bumpus net. It is a small-sized net, designed to be towed at slow speeds, which contains both a closing device and a flow meter. The instrument consists essentially of a brass tube, five inches in diameter and about six inches long, to which may be attached small silk or nylon nets of any desired mesh. The Clarke-Bumpus sampler can be used for either oblique or horizontal hauls, and it can be modified to take vertical hauls. It can be used singly or in series of several nets attached to the same cable at any desired interval.

This sampler is a small net, designed to collect moderate amounts of plankton. It can be used in freshwater as well as marine habitats. It has definite advantages over standard plankton nets in problems that do not require large volumes of plankton. Wiborg (1948) compared the performance of the Clarke-Bumpus sampler with both a centrifugal plankton pump and a standard Nansen closing net, and found the Clarke-Bumpus sampler more satisfactory in most respects. The Clarke-Bumpus sampler has the limitations inherent in any sampler towed at relatively slow speeds and used for short distance rather than continuous sampling. It is described by Clarke and Bumpus (1950).

Hi-Speed Samplers - For some years I have been concerned with the problem of the quantitative sampling of fish eggs and larvae. The patchiness characteristic of the distribution of holoplankton is accentuated in the distribution of fish eggs and larvae. Furthermore, the quantitative sampling of fish larvae presents several perplexing problems, not the least of which is the ability of many of the large larvae to "dodge" a slow moving net during daylight hours. Standard plankton nets are attached to a towing wire by a bridle about 5 meters long, and it is quite likely that both the towing wire and the bridle act as scares. Hence, to prevent dodging it was desirable to devise a net that would precede the towing wire rather than follow it, and one that could be towed at high speeds. To obtain a more representative sample, it was necessary to devise a sampler which could be hauled over considerable distances. To take depth distribution as well as horizontal distribution into account, the samplers should be usable in series, and a suitable depressing force applied to maintain the instruments at the desired depths. Furthermore, it was necessary to have some means of metering the water entering the net, and desirable to have a method of recording the depth at which the net fished. We constructed a pilot model of a hi-speed net which fulfilled about half of the above requirements. It had a flow meter, but no depth meter. By using the expedient of attaching the net to the end of the wire it was possible to have the mouth opening (1" in diameter) precede the wire. The net could not be used in series, nor could it be sunk to any depth. It was limited to horizontal tows near the surface. Within its limitations it performed exceedingly well. Nothing iniitsppath dodged it. Slender fish, 8 or 10 inches, were taken on several occasions when met head-on by the net. This type of hi-speed net would still be valuable for reconnaissance work.

It was at this point that we threw the problem of devising a more adequate hi-speed sampler into the hands of John Isaacs. He has developed a hi-speed net which fulfills all of the requirements I have listed above, and for good measure he has developed a depressor for use with the hi-speed nets which has already been found to have many other uses.

The Isaacs hi-speed sampler is a streamlined tube containing a net and a depth flow meter. Water enters the sampler through a 1" forward opening, is filtered by the net, passes around and activates the meter and is ejected astern. The sampler has been so constructed that it precedes the cable by about a third of its length. The forward end of the sampler is divided so that it may be slid through the cable to an attachment point. It is fastened to the wire by a spherical cable clamp.

The depth flow meter gives a continuous record on 35 mm. clear acetate film of the depth of the sampler in the water, and the flow of water through it. The principal components of the depth flow meter are (1) an impeller and gear train, (2) a pressure element similar to that used in a bathythermograph with attached stylus, and (3) the recording spool and film.

One problem faced with all hi-speed gear is how to get the gear to sample at depths below the surface. To get a net down to even moderate depths, such as 20 to 30 meters, requires considerable depressing force. To solve this need, a homogeneous bronze depressor was developed. The depressor was designed so that it could be operated at several speeds without changing its characteristics. From experience gained on early experimental models made of wood or concrete, it was found essential to construct depressors out of material impermeable to water, to prevent unbalancing and erratic action by the depressor. An unbalanced depressor can be a very dangerous object, indulging in such erratic behavior as flying out of the water and even sailing over the ship. When it again hits the water it is likely as not to dig in with such force as to sever the cable. The bronze depressor has proven to be an exceptionally stable depressor. It will be surprising if it is not put to a variety of uses in oceanographic research.

The Isaacs hi-speed samplers are ordinarily towed at the regular cruising speeds of the oceanographic research vessels on which they are used (8 to 12 knots). We have used them in series of 4 nets, spaced to sample at 10, 20, 30 and 40 meters actual depth. The samplers obtained an integrated horizontal "strip" sample over the distance hauled, usually about 10 miles. About a cubic meter of water is strained by each net per mile of distance towed.

The Isaacs hi-speed sampler has as few limitations as any hi-speed sampler yet developed. Since the samplers can be used in series, an integrated picture can be obtained of horizontal and depth distribution in the upper layer. It can be hauled for as long as 8 or 9 hours with one loading of film, although hauls of this length are not made ordinarily. In trial tests, the organisms have come up in good condition after this length of hauling, many still living. This sampler is not as rugged as some samplers, and it has to be treated with care, but this is true of most good oceanographic instruments. This net is described by Isaacs et al (manuscript).

## SAMPLING OF PHYTOPLANKTON AND BACTERIA

Adequate sampling of the phytoplankton population has always posed problems. How can we obtain an adequate estimate of the standing crop? How best determine the production of organic matter by a given standing crop? The latter problem is briefly discussed in the section titled "Carbon-14".

Obtaining reliable estimates of the standing crop of phytoplankton depends only in part on instrumentation. The adequacy of any estimate of a plankton population depends in large part on the intensity of coverage both in space and time. Intensive coverage in space is needed because of the patchiness in the distribution of phytoplankton. C.E. Lucas (1940) in his discussion of the phytoplankton collected with the Hardy continuous plankton recorder stresses the patchiness in the distribution of phytoplankton. Although he found that some dense patches of phytoplankton occupied areas at least ten miles in extent, smaller patches were observed that were probably less than a mile in extent. Other workers have emphasized the tendency of phytoplankton to clump even with very limited areas. A continuous record, such as that obtained by the continuous plankton recorder, would have definite advantages over "spot" sampling if we could resolve some of the limitations of this method (for a discussion of these, see Lucas, 1940). In investigations using "spot" sampling, consideration should be given to ways of increasing the intensity of coverage. This probably will involve sampling while underway, as well as at stations. Perhaps a modification of the Spilhaus sea sampler, designed to take larger samples, could be developed for sampling while underway. From a stationary vessel, the problem is simplified, for any of a number of standard water-collecting devices may be used to collect phytoplankton samples at a number of depths. To list a few of these, the Nansen reversing water bottle, the Kemmerer water sampler, or the Allen phytoplankton bottle are all effective for trapping a sample of water at any desired depth.

Due to the small size of many kinds of phytoplankton, there is a problem in concentrating samples of these marine plants without loss. Nets are unsatisfactory, for there is considerable loss through even the finest mesh used in nets. Although retention is more complete when the concentration is done by vacuum filtering, using filter paper, sand, or adsorptive powders, there is some loss, and the technique is time consuming. Previously, the best retention has been obtained by centrifuging, but with the recent refinement of the molecular filter membranes, discussed below, there is now available an effective method of concentrating phytoplankton samples without loss. The analysis of the samples, once concentrated, usually is accomplished by either chlorophyll measurements or by visual counting of cells. Neither method is completely satisfactory for all purposes.

The Molecular Filter - The molecular filter developed by Goetz and Tsuneishi (1951), may prove to be of considerable value in assessing the populations of both phytoplankton and bacteria in marine waters. Molecular filter membranes are not new, rather it is the present state of their refinement that warrants their consideration as recent advances in instrumentation. The membranes are built up from a mixture of cellulose esters which form a submicroscopic sponge-like structure of very uniform interstitial dimensions. It is possible to control these dimensions over a wide range in the manufacturing process, with the result that filter membranes can be made with an effective pore size ranging from 1 to 5000 millimicrons. Another feature of the membranes is the peculiar pore structure, which is very small and uniformly spaced on the top side of the leaf and much wider on the under side. As a result of the pore structure, particle retention is restricted to the surface, and it will be complete if the proper pore size has been chosen. Filtering under vacuum can be accomplished more rapidly with molecular membranes than with paper filters or adsorptive powders. Several types of filters have been developed for use with the molecular filter membranes.

The filters can be used for concentrating and then culturing marine bacteria. The bacteria retained on the upper surface of the thin membrane can utilize a nutrient which diffuses through the pores if it is brought into wetting contact with the opposite side of the film. For culturing bacteria, a blotter the size of a filter membrane can be saturated with a basic culture medium, placed under the membrane in a petri dish and then inverted over a moist towel to prevent dehydration and contamination. This use of the membranes has proven very satisfactory in assessing the abundance of bacteria at various levels in oceanic waters.

Several features of the membranes make them peculiarly useful in assessing phytoplankton abundance. The organisms can be quantitatively separated from the water, and then studied without removal from the membrane. Dr. Goldberg of Scripps has developed techniques for staining the specimens on the membrane, then clearing both membrane and organisms so that they may be examined directly on the filter membranes. He uses a membrane that retains all particles greater than approximately 0.5 u (Type HA, available from the Lovell Chemical Company, Watertown, Massachusetts). The membrane are ruled into squares, which facilitates the estimation of the numbers of organisms present.

Carbon-14 - In studying productivity, more is needed than the static picture obtained from standing crop estimates. The production of organic matter by a given standing crop has usually been investigated by the increase in oxygen of a collected sample of water. Recently, E.S. Nielsen (1951), has reported on a technique used during the recent cruise of the GALATHEA, whereby the rate of productivity is estimated from the fixation of radioactive tracer carbon-14. This new technique appears to be very much more satisfactory than the older method for determining photo-synthetic fixation in water where the planktonic populations are low. Of course, a Geiger counter is necessary for assaying radiometrically the fixation of carbon-14.

This is but one use of a radioactive tracer compound in biological research. Radioactive tracers are being used in so many ways already, and offer such potentialities for further advances, that this is certainly one of the most promising fields in research.

## NEW METHODS OF SAMPLING THE NEKTON

Midwater trawl - The most persevering collectors of the larger marine organisms are fishermen and sportsmen. Biologists, particularly fishery biologists, are quick to take advantage of the collecting skill of commercial fishermen for obtaining material needed in many of their research problems. They are also likely to adopt the collecting gear and methods of the fishermen, as well. Hence, until recently, the gear mostly employed in collecting bathpelagic species at mid-depths was the otter trawl, a widely used fishing trawl. However, the otter trawl in its role as a midwater trawl is not particularly satisfactory, and the need has long been felt for efficient collecting devices specifically designed to sample the bathypelagic fauna. There is little need to point out that the fish and other animals that inhabit the mid-depths of the ocean are very imperfectly known.

The Isaacs-Kidd (1951) midwater trawl, developed at Scripps, breaks away from traditional trawl design. The heart of the new trawl is a wide, V-shaped, rigid diving vane that has sufficient depressing force to get the net down to considerable depths (the new trawl has been successfully tested to depths of approximately 12,000 feet), and sufficient stability to maintain the net at a predetermined depth at comparatively high ship speeds (up to about six knots).

Two sizes of trawl have been constructed - a 10 foot trawl and a 15 foot trawl. The smaller-sized trawl, of which several models have been built, has been extensively tested. The vane of this model, made of 1/8 inch steel plate, weighs only about 150 pounds, has a spread of 10 feet, and an area of 21 square feet. The net, especially designed for use with the diving vane, is about 31 feet (182 meshes) long, with a mouth opening of approximately 87 square feet. The mesh used has been $2\frac{1}{2}$ inch stretch, with smaller-sized netting used as liner. The towing bridle has three points of attachment - at either end of the vane it is attached to short, hinged side arms, and at the top of the net it is attached to a $6\frac{1}{2}$ foot spreader bar. For handling the trawl, an A frame has been used on one of the Scripps' vessels, the HORIZON. With the aid of this frame, the trawl can be used in heavier weather than would otherwise be possible. The trawl has been very successful in taking a variety of bathpelagic animals, many of which previously had been unreported for the eastern Pacific. It is being used on the current Scripps expedition into equatorial waters.

Electrical Fishing - The possibility of using electrical methods in the collection of fish is being investigated in several countries. Fish respond to a pulsating direct electric current by orienting to face the anode and swimming toward that pole in a forced manner. By this means it may be possible to lead fish into nets or traps, or to capture them by pumps. As large fish react more vigorously than small fish, selective fishing should be possible.

Research on electrical methods of fish collection is still in the developmental stage. There have been a number of reports of electrical fishing experiments being conducted by German and Russian investigators. A Russian investigator, N.F. Chernigin, claims to have taken 2500 pounds of salmon in 11 hours by using a combination of an electrical field and a pump. This experiment was conducted in a river, however. The German engineers, Kreutzer and Peglow, have been trying to perfect a technique for using electric methods in conjunction with otter trawls in marine fisheries. My knowledge of these experiments is confined to several press releases, and I can't state how successful they have proven.

Groody, Loukashkin and Grant (1952) have recently issued a preliminary report on the behavior of the Pacific sardine in an electrical field. Their research thus far has been conducted on a laboratory scale, but it is felt by the workers that the application of the principles involved to electrical fishing methods in marine fisheries may prove of considerable value. However, they indicate that the problems of instrumentation in this field will be challengingly difficult. It should be noted that some investigators are sceptical whether electrical fishing methods can ever be adapted to marine situations.

## SAMPLING BENTHIC ORGANISMS

Bottom animals are sampled by various types of dredges, grabs, snappers, and coring devices such as the Petersen and Ekman grabs, the Ross snapper, or the Kullenberg piston corer. Dredges and grabs are used for the quantitative or qualitative sampling of the larger benthic organisms; small snappers and coring devices are quantitative only for microscopic organisms such as foraminifera and bacteria. Some of these instruments are designed primarily for taking specimens of the sea-bottom sediments, and as such will be discussed in another part of this symposium. Others, like the Ekman and Petersen grabs, have been widely accepted for many years.

A new type of deep-water dredge has been developed at Scripps. This instrument is a logical adaption of the principle of the Isaacs-Kidd midwater trawl for bottom sampling. The instrument seems very promising, but as it has not been thoroughly tested, it is as yet premature to discuss its merits or defects.*

A bottom sampler described by N.A. Holme (1949) has two cutting cylinders which operate in opposite directions, the thrust of one working against the other.

Other instruments for observing benthic organisms will be discussed in succeeding sections (see especially section on underwater photography and self-contained diving units).

## MISCELLANEOUS INSTRUMENTS

Sonic Devices - Several oceanographic instruments, designed primarily for other uses, are being successfully employed in studying the distribution and abundance of animal populations. In this category are various sonic devices and photographic instruments.

As Johnson (1948) pointed out, there are two principal ways in which sound, depending upon its origin, may serve in biological studies. The sounds produced by marine animals, such as shrimp crackle and the drumming of sciaenids, may be picked up on hydrophones, recorded if a permanent record is desired, and analyzed with appropriate equipment.

Sound, projected as signals from echo-ranging or echo-sounding gear, may be returned as reflected sounds by organisms.+ The "deep scattering layer", a sound-reflecting zone, has been so much discussed since it was first observed in 1942, that it is familiar to anyone interested in oceanographic research. It is generally assumed that the scattering is of biological origin, inasmuch as it is not stationary at any depth, but behaves "biologically" in performing vertical diurnal migration in much the same manner as many planktonic animals. The DSL, which occurs at depths of 150 to 450 fathoms during the daytime, is thought to be caused by stratification of either planktonic animals (such as euphausiids) or nektonic forms associated with the plankton (such as squid or lantern fish).

Lack of adequate instrumentation, particularly gear designed for quantitative sampling of the animals within the sound scattering layer (or layers), has delayed the solution of this problem. The simultaneous use of several deep water trawls sampling different levels should aid materially in the identification of the organisms responsible for the scattering, if the scattering is due to nektonic forms.

Sonic gear, especially echo-sounding gear, is often used in the location of fish schools. In Norwegian fishery investigations, for example, echo-sounding gear has been employed since 1935 in studying distribution of herring, with outstandingly successful results. Hodgson (1950) and other European scientists claim to have developed means of distinguishing the echoes of different species of schooling fish - such as sprat, herring, mackerel and cod. Hashimoto (1951) reports the use of echo-ranging gear for determining the speed of swimming fish schools and the sinking rate of nets. Both echo-ranging and echo-sounding gear have been employed in studying the problem of "availiability" of the Pacific sardine. Even so, not nearly enough use has been made of sonic gear in biological investigations.

---

* - Editorial note: Since the symposium this dredge has been used with success on the Trans-Pacific and other cruises to depths of 3200 fathoms.

+ - In a recent paper, Cushing, Devold, Marr and Kristjonsson (1952) have summarized current research on the use of echo-sounding, echo-ranging and aerial-scouting in fish detection.

Underwater Photography - Underwater camera equipment is usually built around a camera of conventional design which is enclosed in a water-tight box with a glass window. There are now several commercially built underwater cameras on the market. The Benthograph, designed at the University of Southern California, and the Bathygraf, engineered by Cousteau, are recent developments in submarine photographic instruments.

Ewing, Vine and Worzel (1946) have pointed out that the principal problems in underwater photography are not optical in character, nor of camera design. Rather, the problems concern the use of the equipment: finding an interesting subject, putting the camera in focus with it, keeping the camera reasonably steady while the exposure is made, and providing adequate illumination. Except in the littoral zone, where the investigator may accompany his equipment the problems noted above can best be solved when taking photographs of the ocean floor.

Pictures made of the ocean bottom usually are found to contain interesting information on the animal life present on and immediately above the bottom. Over much of the ocean floor, photography is the only simple method of observing and taking a census of the benthic fauna. However, I have been assured by persons who have examined large numbers of such photographs that although some are excellent, many others are tantalizingly inadequate - just about, but not quite good enough for identification of the organisms present. A further limitation of this technique is that it can reveal only those animals which are exposed on the surface. The vast assemblage of animals hidden beneath the surface cannot be assessed by underwater photography.

There is considerably more trouble finding suitable subjects for photography in the oceanic province. Pictures made at random in mid-depths are almost certain to be blank. Hence, photography in this zone may prove of most value in places where organisms are concentrated - such as in fish schools. Investigators have experimented with manned devices, such as the Bathysphere and the Benthoscope, but these have proven to be more spectacular than successful.

Underwater television equipment may become an aid in underwater observation of marine animals. A pioneer use of such equipment was made in 1947 at Bikini Atoll in depths of about 100 feet. More recently further development of underwater television is being engineered in Great Britain, supported by a grant from The Treasury. This project is still in the developmental stage, since the grant was authorized only last year. If such gear can be perfected it should be an invaluable aid in determining the kinds of schooling fish, etc.

Self-Contained Diving Units - A time honored technique of biologists has been the visual observation of animal populations in situ. The development of self-contained diving gear has put an invaluable tool into the hands of ecologists wishing to study animals in their natural environment. The Aqualung, one of the more popular units, employs compressed air bottled at 200 atmospheres. It is strapped to the swimmer's back, and allows swimming about unhampered by hoses or lines for as long as an hour and down as deep as 300 feet. Captain Jacques Cousteau has been active in developing this type of gear and in encouraging its use in ecological studies. In an investigation of the fauna associated with kelp, being conducted at Scripps, most of the observations are made under water by a scientist equipped with a diving unit.* The underwater camera is also an essential tool in such investigations.

## NEEDED BIOLOGICAL INSTRUMENTATION

What is needed in biological instrumentation? I have already touched upon, in the text, some of the instrumentation needed for locating, identifying and sampling the more actively swimming organisms. Electrical fishing, which seems to offer considerable promise, is still in the developmental stage. In the same category is the possible use of television for studying the distribution and abundance of pelagic and bottom organisms. Gear is needed for effective sampling of the larger organisms, fish and squid, in the mid-depths of the ocean. Perhaps larger trawls of the type devised by Isaacs and Kidd may offer a solution to this problem. A challenging problem is some means of identifying the deeper schools of fish recorded on echo-sounding instruments. Eventually, it may be possible to identify schools of fish from the type of pattern that is recorded on echo-sounding instruments, but in order to establish such a relationship it is first necessary to sample, or, by some other means such as underwater photography, identify the schooling organisms.

One of the pressing needs in the field of plankton research is for hi-speed samplers capable of taking deep tows. A limitation on all hi-speed gear developed to date is the shallowness of the layer that can be sampled with the gear. The Hardy plankton recorder is designed to tow at 10 meters depth. The Isaacs hi-speed samplers cannot be gotten much deeper than 50 to 60 meters when used with a single depressor on $\frac{1}{4}$" cable. Even by using special wire and greater depressing force, it is unlikely that the sampler could be gotten much deeper than 100 to 150 meters. This is not deep enough to sample the deep scattering layer, for instance. The development of self-propelled units, entirely freed from dependence on towing cable, may be a possibility.

Another need is instrumentation for studying patchiness in the distribution of plankton. The only sampler now available that can be effectively used in studying this feature is the Hardy plankton recorder. This instrument gives a record at one depth only, hence is useful for studying variation in the horizontal component of distribution, but not in the vertical. To include the vertical component it would be necessary to have a type of sampler that can be used in series. It should be possible to construct a hi-speed sampler having a number of small nets which successively could be moved into position during a haul. Several of these samplers used in series, with their operation synchoronized, would supply the type of sampler needed for studying irregularities in the horizontal and vertical distribution of plankton.

A development that is being given considerable thought by workers at Scripps is an instrument that will take a sample of the bottom mud and the water immediately above, without disturbing the mud-water interface.

---

* - The Aqualung now is being widely used by scientists in all parts of the world. The interesting book by Captain J.Y. Cousteau (with Frederick Dumas), "The Silent World", has drawn the attention of the general public to the adventure of undersea exploration with the Aqualung. George Hetzel, (1953) of Scripps Institution of Oceanography, has put out a useful repair manual for the Aqualung.

No instrument would be so warmly welcomed by investigators handling routine plankton collection as would a mechanical plankton sorter. In our studies of sardine recruitment, for example, we examine several thousands of plankton collections each year for fish eggs and larvae. The separation is now done by a group of laboratory aids, examining each sample under a low-power microscope.

Considerable experimentation has been done on mechanical separation of fish eggs and larvae from the plankton, but without marked success. One of the instruments developed was called an elutriator. Elutriation, as the name implies, is an attempt to obtain a separation of plankton organisms by washing in water, the separation being effected by difference in specific gravity and buoyancy of the organisms. The device, designed by Isaacs and Folsom, introduces plankton organisms slowly into a cross current, allows a sufficient distance of travel to obtain a stratification of the material due to differences in buoyancy, and then effects a recapture in a series of compartments, Although the elutriator was fairly effective in separating out certain plankton groups, such as euphausiids, the separation of fish eggs and larvae was to partial to be of value in our work. This is unfortunate, for the elutriator was a wonderfully ingenious device.

On the basis of our experience it is clear that considerable preliminary experimentation will be needed to develop methods for mechanically separating plankton. It may be found that one process will be sufficient for accomplishing a separation, but in all probability it will require two or more. Once the technique is established, an instrument may be designed to effect the separation.

## DISCUSSION: Gordon A. Riley

It seems to me we have made considerable strides, which you (Dr. Ahlstrom)*have summarized very well, in the basic problem of sampling a local water mass and describing the populations and the biological events therein. We have largely failed to make use of the opportunities afforded by present day physical oceanographers for rapid coverage of large areas. The available information on local variability of physical properties, and what little we know about plankton patchiness, make it apparent that routine methods, with stations some miles apart, are largely inadequate for analyzing processes of physical dispersal of organisms and inorganic nutrients. Closely spaced collections for biological and chemical study obviously create large demands for manpower and ship space. Indeed these demands are so large that such work probably never will be of the greatest aid in evaluating the biological role of horizontal water movements.

Since you have discussed the need for instruments that will demonstrate zooplankton patchiness, I shall say nothing further about that aspect of the problem. The chemists and phytoplankton investigators require an automatic sea sampler of the type now in use but of much larger capacity. I would say that an instrument taking five 500 milliliter samples between the surface and 150 meters would be adequate, although near the minimum limits as to both capacity and depth range.

---

* - Dr. Riley, who was unable to attend the symposium, made his comments on Dr. Ahlstrom's paper in a letter to the author, which is reproduced in part.

For example, with some reduction in the quantity of water used but avoiding micromethods, it would be possible to determine salinity, phosphate, nitrate, , nitrite, silicon and oxygen with 400 milliliter of water and have 100 milliliter left for a cursory examination of phytoplankton. In this connection I should mention a recent paper by Jerlov (1951) on the measurement of particle distribution in the sea, based on the photometric determination of the intensity of a Tyndall beam. I think this method could be used in oceanic waters well away from shore as a gross indicator of the quantity of plankton, since Jerlov has shown that the scattering is mainly from particles of greater than 3 microns. The method would replace chlorophyll determinations and other such methods that ordinarily require large quantities of water and a time-consuming filtration process. Jerlov's discussion and work that I have recently done on the relation between plankton and extinction coefficients indicate that the phytoplankton primarily scatters light rather than absorbs it. The relation with the volume of plankton therefore is of a peculiar form, but the deviation from the mean curve is no greater than, for example, in comparisons of chlorophyll determinations with estimated phytoplankton volumes as determined from cell counts and measurements.

Thus the phytoplankton work on such a cruise would comprise (a) a generalized estimate of the quantity of particulate matter; (b) the same water could then be preserved with formalin for later microscopic examination. Complete counts are neither feasible with such large numbers of samples nor possible with such small volumes of water. But a mere 15 minutes examination would be sufficient to reveal major aspects of species composition and population size. More complete work could perhaps be done on surface bucket samples.

## DISCUSSION: George L. Clarke

## PLANKTON SAMPLING EQUIPMENT

Dr. Ahlstrom has given proper emphasis to the unavoidable selectivity of plankton nets. Comment could also be made on the fact that some organisms show a differential avoidance of the net according to whether the hauls are made during the day or during the night. During the daytime there is a difference in avoidance between nets hauled near the surface and those hauled at such depths that the nets cannot be seen due to the lack of light. It should also be mentioned that the effective pore size of the nets changes with age during the life of the net and also changes during the course of each haul as clogging progressively occurs.

Hardy Plankton Recorder - We tested two of these instruments at Woods Hole and found that the conical timing device was rather inconvenient. Perhaps this part of the instrument has been improved. Once the instrument is assembled and put in running order it can be handled by the crews of merchant ships but the servicing of the instrument before and after each run must be done by experienced technicians. As Dr. Ahlstrom has pointed out the copepod plankton and smaller forms were so badly crushed by the rolled up filtering band that many of them were impossible to identify. The identification of the plankton is extremely laborious. However, the fact that so many of these instruments are being used from the British laboratories at the present time indicates that this objection must be sufficiently overcome. Technicians who are either exceedingly skillful, exceedingly patient, or both, must be employed in making the counts and identifications. This instrument is designed for towing at a single depth only. However, the recorder could perhaps be arranged with an oscillating paravane causing the instrument to change its level periodically and thus sample a stratum of water. Several of these instruments could be towed at several depths simultaneously, thus recording both the vertical and horizontal distribution of the plankton. Although it would obviously be very difficult to cause the recorders to tow at great depths from vessels traveling at cruising speeds, it should be possible to sample the deeper levels from research vessels traveling at slower speeds. At speeds of 2 to 4 knots five instruments could probably be towed at five different depths.

Clarke-Bumpus Plankton Sampler - Over 150 instruments of this design have been built and supplied to more than 60 laboratories in various parts of the world. The plankton sampler has been reported to be very useful at least for certain types of work with certain types of plankton. In addition to whatever intrinsic merit the instrument may have, it has the advantage that it represents a standard quantitative procedure available for every laboratory and makes possible an exact comparison between the results of plankton investigations in different parts of the world. The revised account of the sampler published by Clarke and Bumpus (1950) gives further information for the adjustments and calibration of the instrument. Additional refinements have been developed since 1950, and anyone having any difficulty with the operation of the instrument should consult the authors or the maker.

Two minor difficulties have been reported in the use of this instrument. In regions where jelly-fish, salps, or sea-weed is abundant these organisms may cling to the wire and interfere with the operation of the messengers. The other difficulty is the failure of the instrument to catch a sufficient quantity of plankton in regions where plankton is not abundant. It is believed that a scaled up model of the instrument could be built for such areas. By increasing the opening of the net to a diameter of about 11 inches, the area of the opening and hence the volume filtered per unit of time could be increased fivefold. In the case of larger instruments it would be desirable to streamline them to reduce horizontal resistance if this is feasible.

In our plankton studies on Georges Bank off Cape Cod plankton samplers equipped with No. 2 silk net were hauled at speeds of about 2 knots for periods of 25 to 40 minutes. Ordinarily between 10 and 20 cubic meters of water were filtered during each tow by each sampler. But filtered volumes as high as 30 cubic meters were recorded and, in the case of severe clogging, the filtered volumes were reduced to as little as 5 cubic meters. On Georges Bank the tows with the plankton sampler produced catches of about 1 cubic centimeters of plankton measured by displacement per cubic meter of water filtered, equal to about 1 gram wet weight or 0.1 gram dry weight. Ordinarily 10 to 20 cubic centimeters of plankton were obtained per haul and this amount is obviously sufficient for a quantitative estimation of the more abundant constituents of the plankton. In regions where the plankton is much less abundant, or for a study of the very scarce constituents of the plankton, larger volumes are needed. In such situations the sampler must be towed for longer periods or a larger model must be built.

Comparison with simultaneous hauls made at the same time with larger nets indicated that organisms of the size and activity of sagittae and copepods did not escape the relatively small opening of the instrument in any selective fashion. The plankton sampler can be towed for as long as is desired, thus avoiding the objections of spot sampling. Even with relatively short hauls the sampler obtains a far more representative picture than that obtained by many other methods. In fresh water the sampling of zooplankton is sometimes done by means of water samples taken directly or by means of the Juday plankton trap. Vertical net hauls are of course spot sampling as far as the horizontal direction is concerned. The use of the plankton pump is favored by some laboratories and in this case plankton is obtained from an exceedingly restricted area. The advantages of the plankton pump for certain conditions should not be overlooked. In certain regions where the phytoplankton is very thick no plankton net can give a reliable picture of the zooplankton because of the almost immediate clogging of the pores of the net by the diatoms. In such cases the most reliable measurement of the zooplankton is obtained by means of the plankton pump as described by Wiborg (1948). In situations where excessive clogging occurs if a plankton pump is not available, the plankton sampler must be used with very short hauls only. When clogging is excessive, it is indicated by the counter not turning or turning backwards. Clogging can be minimized by using the coarsest net which will still retain the species of zooplankton to be studied.

A new device for the continuous sampling of plankton at five levels has been described by Tonolli (1951). It is called the plankton bar and has been used on Italian lakes. It is doubtful whether this device could be used in the ocean but it might be serviceable in very restricted, quite waters, such as fjords, estuaries, and salt ponds. The plankton bar consists essentially of five plankton nets towed at five levels simultaneously from one cable. To the tail of each net is attached a rubber tube which leads to the surface where it discharges into a vacuum chamber and there the plankton is collected continuously. This device appears rather complicated but it is perhaps too early to judge the possibilities of the ingenius new development.

High speed Samplers - The "hi-speed" sampler developed at Scripps Institution is obviously a great step forward in zooplankton research. The many good features of the instrument have been described in Ahlstrom's manuscript. Every effort should be made to publish a description of this sampler and an account of its performance.

## SAMPLING OF PHYTOPLANKTON AND BACTERIA

In the opinion of many workers the only feasible method of obtaining phytoplankton on a quantitatively exact basis is through the use of water samples. This is spot sampling in the extreme and criticized in the preceding section. The Hardy continuous plankton recorder has been used for phytoplankton as well as zooplankton for years and its possible more extensive use in other parts of the world should not be overlooked.

A great deal of Harvey's excellent work was done with a net for the collection of phytoplankton. Any net fine enough to retain the phytoplankton will clog very rapidly. Hence, this is perhaps the most likely place to use the plankton pump; where the sea conditions and the depth of the water are such as to make this feasible. In every situation in which individual water samples can be shown to be adequate for determining the population, they are obviously the simplest method to use.

I would like to comment further on methods of estimation of phytoplankton catches in the laboratory. There is much to be said in regard to chlorophyll measurements. A great deal of work has been done by means of centrifuging the water samples and although subject to possible criticism, much of this work seems to be fundamentally reliable. The continuous centrifuge is a possible method for certain purposes. This type of centrifuge has been used chiefly in fresh water, but there is no reason why it should not be more extensively employed for marine investigations.

A settling procedure is sometimes used to concentrate plankton as a preliminary to a final centrifuging. In the Scandanavian laboratories, however, the settling technique is employed in connection with the inverted microscope. This method is regarded as the most reliable by workers in these countries.

## NEW METHODS OF SAMPLING THE NEKTON

Midwater Trawl - It is certainly true that the sampling of nekton at mid-depths is extremely baffling but extremely desirable to attain. It will be recalled that only one specimen of the 5 ft. primitive fish, *Latimeria*, originally caught in 1938 by fishermen off the coast of Africa has ever been obtained,* although great interest was aroused by the taking of this specimen and a reward has been offered for the capture of any other specimens. There are thus evidently large fish at mid-depth about which we know little or nothing. Midwater trawling is also being developed in European water.

Mid-depth purse seining for codfish is being used on a large and expanding scale in the spring fishery at the Lofoten Islands off the northwest coast of Norway. The seines are 200 fathoms long, 40 fathoms deep, and have a 2 inch mesh. When the fishing boat has located a concentration of cod by means of its echo sounder, it shoots its net in a wide arc. When the circle has been completed, the whole net is sunk by means of extra weights to a depth that is determined by the length of the lines from the top of the net to large buoys. The bottom of the net is pursed up immediately, the extra weights are cast off, and the net in the form of a hemisphere floats to the surface. The seine is then shortened until the fish can be dipped out. As much as 100 tons of fish may be taken in one haul. This method of mid-depth fishing should be tried out in other waters in conjunction with the sonic location of fish.

## SAMPLING BENTHIC ORGANISMS

I would like to make further mention of the latest design of the Holme's bottom sampler. This instrument has two cutting cylinders that operate in opposite directions. When the instrument reaches the bottom and the cutting cylinders start to operate, the thrust of one works against the other, thus minimizing the tendency of the instrument to be displaced. With only one cutting cylinder, the instrument may be slid along the bottom instead of having the cutting edge dig in as it should. Good success has been obtained with a commercial type clam shell bucket and also with an orange peel dredge in work undertaken from Woods Hole.

## MISCELLANEOUS INSTRUMENTS

Self-contained Diving Units - In August 1951 an expedition left Lowestoft, England, for the Mediterranean. In the exceedingly clear water of the Mediterranean on light-colored bottoms, it was planned to use commercial otter trawls and to photograph their action underwater by means of self-contained diving units. Any photographs or moving pictures obtained by this expedition will be extremely valuable in determining the effective size of the mesh, the height and position of the net in fishing on the bottom, and the action of the foot rope in digging up the bottom, and hence possibly destroying the food organisms there.

---

* - Editorial note: Since this paper was written, an additional specimen, in better condition, has been taken.

## REFERENCES: Ahlstrom

ANDERSON, A.W., and LYMAN, JOHN. 1952. "Oceanographic Instruments, Their Use and Application in Marine Biology". *Gulf and Carib. Fisheries Inst., Proc., Fourth Annual Session. pp. 103-110.*

BOSSANYI, J. 1951. "An Apparatus for the Collection of Plankton in the Immediate Vicinity of the Sea-Bottom". *Jour. Marine.Biol. Ass. United Kingdom, Vol. 3p, no. 2, pp. 265-270.*

CLARKE, G.L., and BUMPUS, D.F. 1950. "The Plankton Sampler - An Instrument for Quantitative Plankton Investigation". *Limn. Soc. Am., Spec. Publ. No. 5, revised 1950. p. 8.*

COUSTEAU, CAPT. J.Y., with DUMAS, FREDERIC. 1953. "The Silent World". *Harper and Brothers, New York. 266 pp.*

CUSHING, D.H, DEVOLD, F., MARR, J.C., and KRISTJONSSON, H. 1952. "Some Modern Methods of Fish Detection". *FAO Fisheries Bull. Vol. 5, nos. 3-4.*

DIETZ, ROBERT S. 1948. "Deep Scattering Layer in the Pacific and Antarctic Oceans". *Jour. Marine Res. Vol. 7, no. 3. pp. 430-442.*

EMERY, K.O. 1952. "Submarine Photography with the Benthograph". *Scientific Monthly. Vol. LXXV, no. 1. pp. 3-11.*

EWING, MAURICE, VINE, ALLYN, and WORZEL, J.L. 1946. "Photography of the Ocean Bottom". *Jour. Optical Soc. Amer. Vol. 36, no. 6. pp. 307-321.*

GAULD, D.T, and BAGENAL, T.B. 1951. "A High-speed Tow-net". *Nature. Vol. 168 No. 4273. p. 523.*

GOETZ, ALEXANDER, and TSUNEISHI, NOEL. 1951. "Application of Molecular Filter Membranes to the Bacteriological Analysis of Water". *J. Am. Water Works Assn. Vol. 43, no. 12. pp. 943-948,*

GROODY, TOM, LOUKASHKIN, ANATOLE, and GRANT, NORMAN. 1952. "A Preliminary Report on the Behavior of the Pacific Sardine (Sardinops Caerulea) in an Electrical Field". *Proc. Calif. Acad. Sci. 4th. Ser. Vol. XXVII, no. 8. pp. 311-323.*

HARDY, A.C. 1936. "The Continuous Plankton Recorder". *Discovery Reports, Vol. XI, pp. 457-510.* 1939. "Ecological Investigation with the Continuous Plankton Recorder". *Hull Bull. Marine Ecol. Vol. 1, no. 1. pp. 1-57.*

HASHIMOTO, TOMIJU. 1951. "Study of the Ultrasonic Echo-Sounder Fish-Finder and Its Applications". *Fishing Boat Series 2, Fisheries Agency, Tokyo. 150 pp.*

HETZEL, GEORGE F. 1953. "Overhauling the Aqualung". *University of Calif., Scripps Institution of Oceanohrapgy, Oceanographic Equipment Rept. No. 3. SIO Ref. 53-28. 10pp.*

REFERENCES: Ahlstrom Cont'd

HODGSON, W.C. 1950. "Echo Sounding and the Pelagic Fisheries". *United Kingdom, Min. of Agr. and Fisheries, Fishery Investigations Series 2, Vol. 17, no. 4. 25 pp.*

HOLME, N.A. 1949. "A New Bottom-sampler". *Jour. Marine Biol. Assoc. United Kingdom Vol. 28, no. 2, pp. 323-332.*

ISAACS, JOHN D., and KIDD, LEWIS W. 1951. "A Midwater Trawl". *University of California, Scripps Institution of Oceanography. SIO Ref. 51-51. 10 pp.*

ISAACS, JOHN D., AHLSTROM, ELBERT H. KIDD, LEWIS W., and THRAILKILL, JAMES R. 1953. "A High-Speed Plankton Sampler". *(Manuscript).*

JOHNSON, MARTIN W. 1948. "Sound as a Tool in Marine Ecology, from Data on Biological Noises and the Deep Scattering Layer". *Sears Found. Jour. Marine Res. Vol. VII, no. 3. pp. 443-458.*

LUCAS, C.E. 1940. "Ecological Investigations with the Continuous Plankton Recorder; the Phytoplankton in the Southern North Sea, 1932-37". *Hull Bull. Marine Ecol. Vol. 1, no. 4. pp. 73-170.*

NIELSEN, E. STEEMANN. 1951. "Measurement of the Production of Organic Matter in the Sea by Means of Carbon-14". *Nature. Vol. 167, 28 Apr. 1951. p. 684.*

SPILHAUS, A.F., and MILLER, A.R. 1948. "The Sea Sampler". *Sears Found. J. Mar. Res. Vol. VII, no. 3. pp. 370-385.*

SOUND, OSCAR. 1943. "The Fat and Small Herring on the Coast of Norway in 1940 - The Modes of Occurrence of the Herring in the Sea as Revealed by Echo-Sounding". *Annales Biologiques. Vol. 1, 1939-41. pp. 60-72.*

TUCKER, G.H. 1951. "Relation of Fishes and Other Organisms to the Scattering of Underwater Sound". *Sears Found. Jour. Marine Res. Vol X, no. 2, pp. 215-238.*

WIBORG, KRISTIAN FREDRIK. 1948. "Experiments with the Clarke-Bumpus Plankton Sampler and with a Plankton Pump in the Lofoten Area in Northern Norway". *Report on Norwegian Fishery and Marine Invest. Vol. IX, no. 2. 1-32, 1951.* "The Whirling Vessel; an Apparatus for the Fractioning of Plankton Samples". *Report on Norwegian Fishery and Marine Invest. Vol. IX, no. 13. 16 pp.*

WOOD, HENRY, and PARRISH, B.B. 1950. "Echo-Sounding Experiments on Fishing Gear in Action". *J. Cons. Int. Explor. Mer. Vol. XVII, no. 1, pp. 25-36.*

## REFERENCES: G. L. Clarke

**ANDERSON, A.W. and LYMAN, JOHN** 1952. "Oceanographic Instruments, their Use and Application in Marine Biology". *Proc. of the Gulf and Caribbean Fisheries Institute. Fourth Annual Session; pp. 103-110.*

**BOSSANYI, J.** 1951. "An Apparatus for the Collection of Plankton in the Immediate Vicinity of the Sea-Bottom". *Journ. of the Mar. Biol. Assoc. of the United Kingdom, Vol. 30, No. 2, pp. 265-270.*

**CLARKE, G.L. and BUMPUS, D. F.** 1950. "The Plankton Sampler - An Instrument for Quantitative Plankton Investigations". *Limnological Soc. of Amer., Spec. Publ. No. 5; Revised 1950; 8 pp.*

**COUSTEAU, CAPT. J. Y. and DUMAS, FREDERIC.** 1953. "The Silent World". *Harper and Bros. New York. 266 pp.*

**CUSHING, D.H., DEVOLD, F. MARR, J. C. and KRISTJONSSON, H.** 1952. "Some Modern Methods of Fish Detection". "Echo Sounding, Echo Ranging and Aerial Scouting". *FAO Fisheries Bull. vol. 5, No. 3-4, 27 pp.*

**DIETZ, ROBERT S.** 1948. "Deep Scattering Layer in the Pacific and Antarctic Oceans". *Sears Found. Journ. Mar. Res., vol. VII, No. 3, pp. 430-442.*

**EMERY, K. O.** 1952. "Submarine Photography with the Benthograph". *Scientific Monthly, vol. LXXV, No. 1; pp. 3-11.*

**EWING, MAURICE, VINE, ALLYN, and WORZEL, J.'L.** 1946. "Photography of the Ocean Bottom". *Journ. Optical Soc. of Amer., vol 36, No. 6; pp. 307-321.*

**GAULD, D.T. and BAGENAL, T.B.** 1951. "A High Speed tow-net". *Nature, Vol. 168; p. 523.*

**GOETZ, ALEXANDER, and TSUNEISHI, NOEL.** 1951. "Application of Molecular Filter Membrwnes to the Bacteriological Analysis of Water". *Journ. Amer. Water Assoc., Vol. 43, No. 12; pp. 943-984.*

**GROODY, TOM, LOUKASHKIN, ANATOLE, and GRANT, NORMAN.** 1952. "A Preliminary Report on the Behavior of the Pacific Sardine (Sardinops caerulea) in an Electrical Field". *Proc. Calif. Acad. Sci. 4th Ser., Vol XXVII, No. 8; pp. 311-323.*

**HARDY, A.C.** 1936. "The Continuous Plankton Recorder". *Discovery Reports, Vol. XI; pp. 457-510.* 1939. "Ecological Investigations with the Continuous Plankton Recorder". *Hull Bull. Mar. Ecol., Vol 1, No. 1; pp. 1-57.*

**HASHIMOTO, TOMIJU.** 1951. "Study of the Ultrasonic Echo-Sounder, fish-finder and its Applications". *Fishing Boat Series IX, Fisheries Agency, Tokyo; 150pp.*

**HETZEL, G.F.** 1953. "Overhauling the Aqualung". *U. of Calif., Scripps Inst. of Oceanography. Oceanographic report no. 3; 10pp.*

**HODGSON, W.C.** 1950. "Echo Sounding and the Pelagic Fisheries". *(United Kingdom, Ministry of Agriculture and Fisheries) Fishery Investigations Series II, Vol. 17, No. 4; 25 pp.*

## REFERENCES: G. L. Clarke Cont'd

**HOLME**, N. A. 1949. "A New Bottom-Sampler". *Journ. Mar. Biol. Assoc. N.S., Vol. 28; pp. 323-332.*

ISAACS, JOHN, D. and KIDD, LEWIS, W. 1951. "A Midwater Trawl". *Univ. of Calif. Scripps Inst. of Oceanography, Ref. 51-51, Nov. 15, 1951; 10 pp.*

ISAACS, J. D., AHLSTROM, E. H., KIDD, L.W. and THRAILKILL, J.R. "A New Type High-Speed Sampler". *Manuscript.*

JOHNSON, MARTIN W. 1948. "Sound as a Tool in Marine Ecology, from Data on Biological Noises and the Deep Scattering Layer". *Sears Found. Journ. Mar. Res., Vol. VII, No. 3; pp. 443-458.*

LUCAS, C.E. 1940. "Ecological Investigations with the Continuous Plankton Recorder: The Phytoplankton in the Southern North Sea, 1932-37". *Hull Bull. Mar. Ecol., Vol. 1, No. 3; pp. 73-170.*

NIELSEN, E. STEEMANN. 1951. "Measurement of the Production of Organic Matter in the Sea by Means of Carbon-14". *Nature, Vol. 167, Apr. 28, 1951; pg. 684.*

SPILHAUS, A.F. and MILLER, A.R. 1948. "The Sea Sampler". *Sears Found. Journ. Mar. Res., Vol. VII, No. 3; pp. 370-385.*

SOUND, OSCAR. 1943. "The Fat and Small Herring on the Coast of Norway in 1940 - The Modes of Occurrence of the Herring in the Sea as Revealed by Echo Sounding". *Annales Biologiques, Vol. 1, 1939-41; pp. 60-72.*

TONOLLI, VITTORIO, 1951. "A New Device for Continuous Quantitative Plankton Sampling: The Plankton Bar". *Proceedings of the International Association of Theoretical and Applied Limnology, Vol. 11, Pp. 422-429, 1951.*

TUCKER, G.H. 1951. "Relation of Fishes and Other Organisms to the Scattering of Underwater Sound". *Sears Found. Journ. Mar. Res., Vol. X, Nov. 2; pp. 215-238.*

WIBORG, KRISTIAN FREDRIK. 1948. "Ecperiments with the Clarke-Bumpus Plankton Sampler and with a Plankton Pump in the Lofoten Area in Northern Norway". *Report on Norwegian Fishery and Marine Invest., Vol. IX, No. 2; 32 pp.*
1951. "The Whirling Vessel". "An Apparatus for the Fractioning of Plankton Samples". *Report on Norwegian Fishery and Marine Invest., Vol IX, No. 13; 16 pp. Fiskeridirektoratets Skrifter Ser. Havundersokelser Repts. Norwegian Fish and Marine Invest.*

WOOD, HENRY, And PARRISH, B.B. 1950. "Echo-Sounding Experiments on Fishing Gear in Action". *Journ. du Conseil, Vol XVII, No. 1; pp. 25-36.*

# OCEANOGRAPHIC INSTRUMENTS FOR MEASURING TEMPERATURE*

Allyn C. Vine

## INTRODUCTION

A great deal of oceanographic effort in the past has gone into measuring ocean temperatures and determining how they vary with location, season and depth. For some problems, such as thermal flow, the measured temperature variations are the primary end. In other problems, temperature variations which are rather easy to measure give excellent correlation with some desired variable which is not easy to measure directly.

Temperature measuring equipment in oceanography has tended to be very simple for several reasons. First, the majority of the experimental oceanographers in the past were biologists rather than physicists or engineers. Secondly, when complicated apparatus was built and used, it usually either failed to work satisfactorily on shipboard or it would only work for the builder. Thirdly, the trend in almost any field work is to adopt the available instruments which give the least trouble and then they soon become the generally accepted instruments.

It is the purpose of this paper to describe some of the temperature measuring instruments which have been used, and the principal types of temperature measuring elements and systems. The principal effort, however, will be placed on trying to analyze the temperature problems we are confronted with, the limitations of present day instruments, and outlining new types of instruments that should be successful in attacking these problems.

## OLDER INSTRUMENTS

Because of the relative ease of measuring temperatures compared to measuring salinity, density, or current, it has remained important not only as an end in itself but also as an indicator. It is presumed that this trend will continue and that temperature measurements will continue to be one of the most powerful and versatile ways we have of figuring out our oceanographic puzzle.

During the years we have gradually accumulated enough temperature measurements to obtain a rough overall picture of the northern Atlantic and Pacific which is reasonably descriptive for large scale phenomena. We are sadly lacking however to describe in a detailed way how thermal exchanges take place or to predict small scale oceanographic features.

Bucket and Thermometer - In order that this paper can have as simple a beginning as quantitative physical oceanography did, let us start out with the use of a bucket and a thermometer. The purpose of emphasizing such a simple piece of equipment is because much good work has been done with it. Bucket temperatures can be either correct or misleading depending upon the degree of thermal layering near the surface and depending upon the skill of the observer and interpreter. The simple bucket and thermometer will probably continue to be a mainstay for calibration purposes for a long time. In the hands of a good experimentalist it is also probable that good research work will be done with it in the future. For example, a modern version of the bucket is to use a hose and to pump water with it from a given depth to the surface.

---

* - Contribution No. 696 from the Woods Hole Oceanographic Institution.

Water Intake Thermometers - Much of our knowledge of horizontal gradients in the ocean has come from a study of intake temperatures on ships. This has seldom given data which permits the study of fine horizontal structure but it would seem that this could and should be done. The sensitivity of the apparatus should be improved as well as the time constant. Practice has indicated that an observer usually has to go with the thermometer to insure that the necessary auxiliary data be obtained.

Reversing Thermometer - From 1870 until 1938 the two principal tools in physical oceanography were the reversing thermometer, to determine temperature, and the Nansen bottle to obtain water samples for salinity and oxygen determinations. This thermometer combined a simplicity of operation, a high absolute precision, and was operable over a wide depth range. Another excellent feature of the reversing thermometer is that when used in protected and unprotected pairs they constitute their own depth gage. These desirable characteristics have made it a standard oceanographic instrument and one which will not be entirely replaced in the forseeable future.

It does not seem necessary to describe the reversing thermometer in detail, as it is well known among oceanographers, and has been described several places in the literature. For the moment let us say that, under ideal conditions reversing thermometers can give temperature to about 0.02° C and depths to about 10 meters. The reversing thermometer, however, suffers from a slow speed of response and from being able to give data at only a limited number of depths.

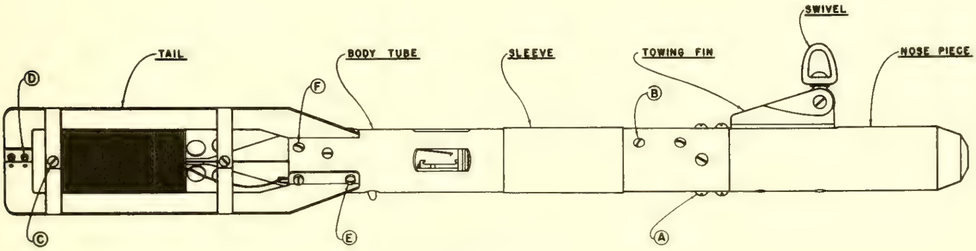
Because the reversing thermometer has become a standard tool in oceanography, it will pay us to critically examine its limitations so that we use them on experimental work for which they are best suited and do not improperly interpret results on experimental work for which they are unsuited.

Because of the nature of the use of reversing thermometers it is doubtful if they will ever be well suited for studying small scale or rapid thermal changes in the ocean. They are excellent, however, for studying the gross features of the ocean and for measuring stable temperatures at great depth. Another virtue of the reversing thermometer is that it has been paired for many years with the Nansen bottle and hence the general utility of each device is greatly enhanced by the presence of the other.

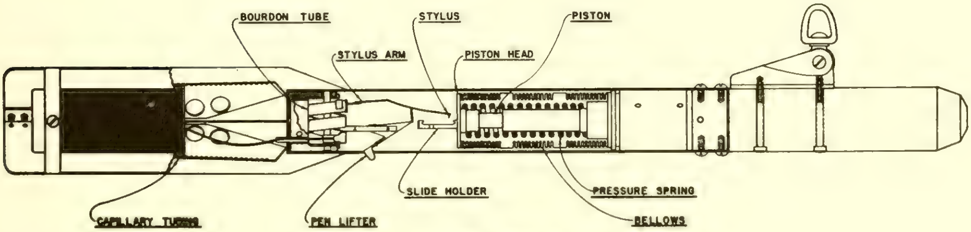
Bathythermograph - For many years there had been a need for a practical device which would make a continuous temperature measurement. In 1938 Spillhaus designed the bathythermograph which was an early practical temperature depth recorder. Furthermore, it was possible to use it from a slowly moving vessel.

In 1940 and 1941, Ewing, Worzel and the writer modified the bathythermograph considerably by adapting the Spillhaus instrument to be used as a diving instrument. The concept of towing a recorder at various depths was abandoned because of the heavy weight, cable and winch required. The emphasis was placed on redesigning the BT so that you dropped it overboard, paid out cable faster than the ship was going and let it fall free. The winch and cable were to retrieve the BT but were not designed to drag it at any appreciable depth and speed. This technique permitted measurements down to 400 feet at 12 to 15 knots on 1/16 inch steel cable, using a winch which only weighed about 300 pounds. It required that the BT be made to dive rapidly and that obtaining high speed of thermal response become the predominate design feature. The additional requirements of simplicity and freedom from vibration decided the choice of a liquid-filled bourdon temperature assembly, using some 50 feet of .020 inch bore by .050 inch O.D. Copper tubing for the thermal sensitive unit. The temperature bourdon was case-compensated with a bimetalic strip to reduce the thermal hystersis of the instrument. With such a system the time for 90% response was decreased to about 4/10 seconds, or about 2/10 seconds to 1/e. Even this is none too good when the BT is dropping at 10 feet per second through a sharp thermocline.

The precision of reading the BT is from .1 to .3°F depending upon how fast the ship is going and on the adjustments of the pen. The depth accuracy is about 1% of full scale. The record is made on a 1 x 1 3/4 inch smoked microscope slide. While the record is small it is capable of being read as accurately as the data on it and it can readily be examined against a calibrated grid with either a 5 power eye piece or a projector. Figure 1 is a schematic of this instrument essentially as it is available on the commercial market.



EXTERNAL VIEW



INTERNAL VIEW

Fig. 1. The Bathythermograph

While the BT is not a particularly complicated instrument its reliability and surprisingly accuracy have vastly increased our knowledge and appreciation of the complexity of the thermal structure of the ocean.

## WHAT SHOULD WE MEASURE?

This section is aimed at showing what a large range of thermal measuring problems exist in the ocean and what a large variety of instruments will be required to solve them. It is also aimed at making us look more critically at the measurements which we take.

Figure 2 is an attempt to show that one can find thermal problems in the ocean of almost any linear dimension in depth one chooses. This figure indicates the various full scale depth ranges one might use for different problems. Figure 2 illustrates several features:

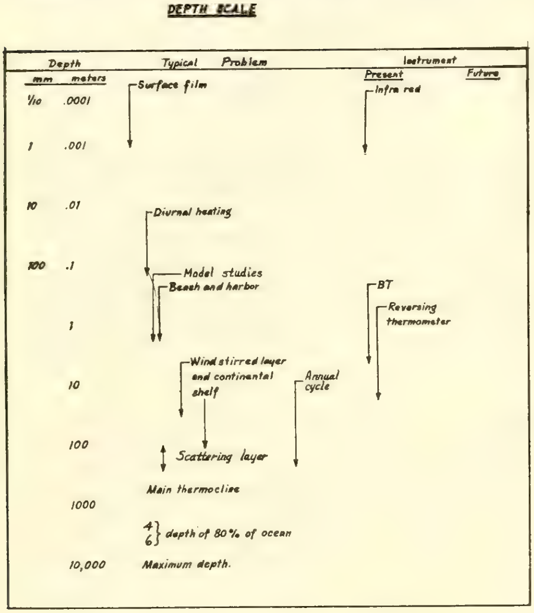

DEPTH SCALE
Depth
mm
meters
Typical Problem
Instrument
Present
Future
1/10
.0001
1
.001
10
.01
100
.1
1
10
100
1000
10,000
Surface film
Diurnal heating
Model studies
Beach and harbor
Wind stirred layer and continental shelf
Annual cycle
Scattering layer
Main thermocline
4
6
depth of 80% of ocean
Maximum depth.
Infra red
BT
Reversing thermometer

Fig. 2. Depth Scale

a. No matter what depth scale one chooses to work over there are other smaller scale phenomena and problems. There are also very apt to be larger scale phenomena.
b. An individual instrument will only cover a farily small range of depths, usually this is from full scale to 1% or possibly 1/10% of full scale. Because of this limitation many problems must be tackled with two or more types of instruments.
c. Attention is called to the logarithmic chart because it infers that the surface (zero depth) cannot be attained. The writer used to be worried about this aspect of logarithmic presentation but he is now convinced that this is an experimental reality with which we must live. The finite size of thermal probes, the characteristic infra red radiation methods, and the general oscillatory motion of the water surface make the true surface temperature something about which we can speculate but can probably never measure. This may seem like a trivial point but to study evaporation problems one may well want to know what is happening in the top few microns.
d. The fact that oceanography involves problems covering a full scale depth range of over 100,000,000 is something we should bear in mind when considering future research problems.

Any division into categories must necessarily be somewhat arbitrary but the writer also suggests the following breakdown of operating depth as the ones which usually affect pressure case design, length of cables, etc.

| | |
|---|---|
| 1. Above the water | Marine meteorology, or the vapor phase of oceanography |

| | |
|---|---|
| 2. Above 1 meter | The surface film<br>Model studies |
| 3. Above 20 meters | The diurnal heating zone<br>Harbor problems<br>Coastal problems |
| 4. Above 200 meters | The wind-stirred layer<br>Continental shelf studies |
| 5. Above 1500 meters | The main thermocline<br>Slope studies |
| 6. Between 4000 to 6000 meters | The depth of most of the ocean bottom |
| 7. Between 6000 to 9000 meters | The oceanic depths |
| 8. Below the bottom | The temperatures within the bottom |

The range in time scales for various oceanographic processes is probably greater than the variation in depth ranges. Figure 3 illustrates in a logarithmic way time scales varying by $10^{17}$. Occasional investigators have worked on problems near the top or bottom of Fig. 3 and these excursions may well have a great influence on oceanographic research; more are to be encouraged.

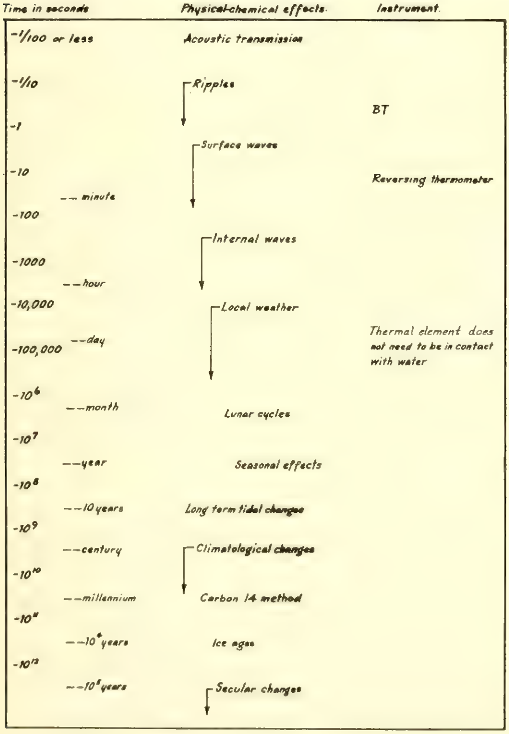

Time in seconds
Physical-chemical effects
Instrument
-1/100 or less
Acoustic transmission
-1/10
Ripples
BT
-1
Surface waves
-10
Reversing thermometer
-- minute
-100
Internal waves
-1000
-- hour
-10,000
Local weather
-- day
-100,000
Thermal element does not need to be in contact with water
-10⁶
-- month
Lunar cycles
-10⁷
-- year
Seasonal effects
-10⁸
-- 10 years
Long term tidal changes
-10⁹
-- century
Climatological changes
-10¹⁰
-- millennium
Carbon 14 method
-10¹¹
-- 10⁴ years
Ice ages
-10¹²
-- 10⁵ years
Secular changes

Fig. 3. Time Scale

To date the vast majority of the thermal work in oceanography has been done in the time range of from one day to one year. Even the periods associated with internal waves have received only a small amount of effort while on the other end of the scale the long range problems have only recently been receiving much attention.

It can be seen from Figs. 2 and 3 that certain depth ranges and time scales are relatively unexplored by virtue of the lack of adequate instrumentation. Recommendations of these instruments will be made in a later section.

## POINT OR CONTINUOUS OBSERVATIONS

In order to properly study and interpret the ocean we would like to get continuous information regarding it. In other words we would like to know not only the temperature at a point but also the time and the three space derivatives of temperature. Now obtaining continuous information in both space and time would present impossible problems of both instrumentation and data handling. We need, therefore, to devise our experiments and instruments so that we obtain as many observations as practical in the most logical manner. It would seem that the criteria of how many observations are needed will depend upon our ability to interpolate between our observed points.

Investigators are apt to become over-confident of their work on the basis of observed points which fit a given assumption. This can be quite dangerous, particularly if the assumption was made after the data was taken. I would like to add a word of caution and recommend that the precision of a set of temperature-depth points be determined by "the reliability and precision of interpolated temperatures" rather than on the temperatures at the measured depths.

Because it is not mathematically feasible to determine the precision of interpolation along an unknown curve, we interpolate from point to point on the basis of an assumed temperature-depth distribution. For example our mind will usually only permit so many inflection points. In other words, our precision of interpolation is intimately connected with how many inflection points we think exist in the actual curve.

In order to arrive at thumb rules for interpolating data of this kind, I would suggest that in areas where the temperature structure is well known and appears linear, we can interpolate to within say 2% of the temperature difference between thermometers. Where the temperature structure is not well known, or is not nearly linear, it is doubtful if we can estimate temperatures to within 5% of the difference between temperatures. In essence, it is emphasized that important small scale fluctuations can exist in the temperature structure of the ocean and escape our present methods of measuring and analysis. I would, therefore, suggest that we tend to think of a temperature-depth trace as a fuzzy band rather than as a mathematical line. Furthermore, we should remember that this band is opaque, and much of the future progress in oceanography will come through learning more about the small scale changes.

Figure 4 shows a set of temperature-depth points with several types of interpretation made on the data to illustrate the points in question.

First, we have a smooth line drawn connecting the points as one would normally do. Second, we have a series of rectangles with opposite corners connecting adjacent points. While a total error as large as the area of these blocks is perhaps ridiculous, we must remember that any one point could make an excursion as great as this without even introducing a reversal of temperature.

Third, we have placed a pair of temperature points midway in depth between observed points assuming that we can interpolate to within about 5% of the temperature difference between points. Then we have drawn a wide line to indicate the extent of the fine structure which may still be beyond the powers of our data to disclose.

I want to emphasize that most of our deep water theories of the ocean have been built up on a mass of data which is incapable of showing fine structure, particularly as usually analyzed.

## ERRORS IN TEMPERATURE DATA

In taking and interpreting any oceanographic temperature measurement we must remember that many factors come in. Components of error are numerous, and oftentimes very subtle. A listing of some of the sources may help

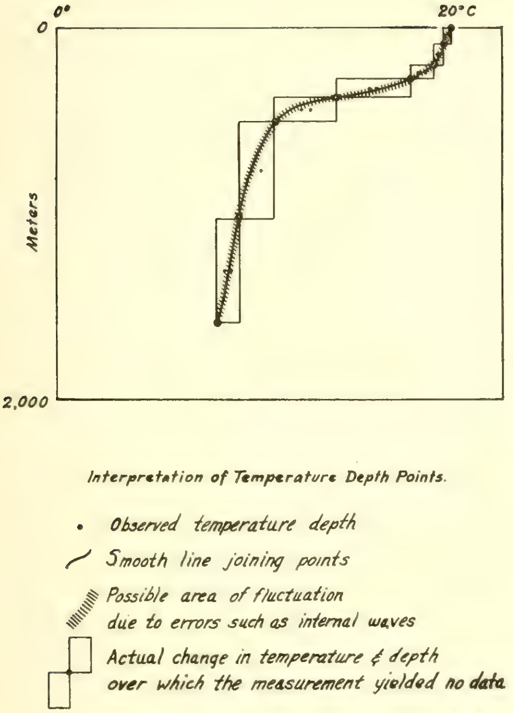


Fig. 4. Typical set of temperature-depth points showing range of possible interpretations.

clarify the problem somewhat.

a. The primary measuring element will have its own internal hysteresis and thermal time constant.
b. The recorder will have its own hysteresis and time constant.
c. The time or depth scale will have its own hysteresis and time constant. These time constants make a low pass filter of the recorder.
d. The phenomena we are measuring may well be changing both spatially and timewise, for example, in the presence of eddies or internal waves.
e. In all probability our measuring instrument is being dragged or is oscillating vertically and horizontally through the structure we are trying to measure.
f. If we are trying to measure small structures we are confronted with the finite size of the measuring probe.

The dynamic size of a thermal element can be many times the actual size and it must be known and understood for each piece of equipment. Instead of the actual size of the probe one should visualize a fictitious temperature element whose size is as large as the actual size plus the product of its thermal time constant times the speed the element is moving through the water. The time constant is the time required for the thermal element to come to within a given per cent of the final temperature. This is usually stated as the time to come to within 37% of the final temperature. In a thermal system the response is usually logarithmic and will have the following response:

| Time | Approach to Final Temperature |
|---|---|
| $\theta$ | 37% |
| $2\theta$ | 13% |
| $3\theta$ | 5% |
| $4\theta$ | 2% |
| $5\theta$ | 0.7% |

A bathythermograph will have a time constant of about 2/10 seconds so if it is falling 10 feet per second its thermal element will be effectively 4 feet long if it is to respond within 13% of the temperature change and effectively 10 feet long if it is to respond to within 7/10% of the temperature change.

It is very difficult to make a rugged thermal element with a rapid speed of response although the state of the art is improving and some commercial manufacturers are making higher speed elements. Even an infra red device will not give true surface temperatures because it will respond to an average temperature of the top few tenths of a millimeter of water.

## THERMAL SENSITIVE DEVICES

When making a thermometer one should think carefully of how temperature affects various substances and structures and select a primary sensitive element which:

a. gives a large output per degreeC. This usually should be measured in units of work per degree;
b. has good thermal stability over the period of time in question;
c. is not unduly affected by pressure;
d. is reliable;
e. has sufficient speed of response;
f. does not have different time constants for different parts of it;
g. is not too sensitive to vibration. Here one wants a short natural period.

The choice of thermal elements is fairly large and a particular application may dictate a particular choice.

1. Thermal expansion of a gas. This will permit large work outputs and is convenient except for its very large pressure coefficient.
2. Thermal expansion of a fluid. This is commonly used and can have good reliability and a large work output. Mercury thermometers and BT's are typical.
3. Thermal expansion of a solid. This has the least motion and most designs have either a slow speed of response or are sensitive to vibration. Bimetallic elements are used in the thermo sonde.
4. Change in the electrical resistance of a metal or conductor. Resistance thermometer bridges are stable, accurate and well understood. Thermistors are certainly coming into their own and while they still lack long time stability they make it possible to build a cheap and sensitive thermal element. Their high resistance makes them very good for inputs to servo amplifiers.
5. Peltier effect - the emf produced by a thermocouple. The power developed in a thermocouple circuit is very small but it is well adapted for comparing temperatures at several different points.
6. Vapor pressure thermometers are widely used in industry and they are based on the vapor pressure of a given fluid.

## INSTRUMENT DESIGN

It is impractical to recommend a specific method without knowing the problem and the techniques available to the builder. Personnel preference, training and ability will usually determine how an instrument is built. The following notes may be of value to designers.

a. Mechanical levers. If the primary measuring element gives a large work output it may be practical to use mechanical levers for amplification. When well done this method is simple and reliable. Such systems are sometimes allergic to vibration. If bearings are used corrosion can be a number one problem.
b. Optical levers. These have the great advantage of giving high magnification and being almost inertialess. Another great advantage is that several traces can be lined up and still overlap.
c. Servo systems. The use of an electrically operated self-balancing bridge is perhaps the most versatile system as it can be operated with very small inputs and can give a large output. Many manufactors produce a wide variety of commercial servo systems.

d. Recording methods. There are several mediums available for recording data and the writer does not pretend to know them all. However several are listed to indicate the range.
   1. Smoked glass has been used with great success on the bathythermograph. Its advantages are high resolution, low friction and ability to withstand exposure to sea water. Its disadvantages of small size and inconvenience of smoke are real but are often of minor importance.
   2. Waxed paper is commercially available, will give high resolution and in some cases will withstand immersion in water. It is usually available in rolls and can be used for long records.
   3. Pencil or ink on paper is very good if the record is large enough. A conventional pencil or ink record on a paper or plastic surface is convenient to work with. Ink suffers from spilling if treated rough or smudging if the pen remains at one place. Most ball point pens will not give satisfactory service at slow writing speeds. A pencil requires a remarkably heavy pressure to give a satisfactory trace.
   4. A photographic record is nowhere near as inconvenient as most people make out. The advent of the Polaroid Land Camera can sometimes further alleviate the problem. Photographic recording has many competitors but is probably the most versatile of all methods which give a visual record.
   5. Magnetic tape can be used for recording temperature data with a wide range of coding schemes.

## TYPES OF INSTRUMENTS WHICH ARE IN THE DESIGN OR TESTNG STAGE BUT WHICH ARE NOT GENERALLY AVAILABLE

One of the difficulties in oceanography is that most instruments seem to be in the design stage and are not generally available. It would appear impractical to more than mention some of the work which is going on as the individual investigator is the only reliable source of information in the early stages of development.

a. Scripps has had considerable experience and luck with their "Thermitow" which was designed to be towed near the surface of the water and record on a commercial electrical recorder on deck.
b. Devik of Norway has used an infra red pick-up to measure horizontal differences in the surface temperature of lakes.
c. Woods Hole Oceanographic Institution has been working on several variations of a recording thermometer which will record for periods of from a week to a year.
d. Several laboratories have considered the problem of a thermometer to be on the bottom of the ocean.
e. Combined temperature and conductivity meters or salinity meters have been built by the Bristol Company, WHOI, Chesapeake Bay Laboratory and the Navy Electronics Laboratory.

## TEMPERATURE RECORDERS WHICH ARE NEEDED

There will be no attempt to recommend which of these following thermometers is the most important, because individual preference would vary widely. It does, however, seem advisable to list a few important instruments which still have to be made and become available.

a. A Rapid Response BT For The Top Few Meters: When studying the near surface problems, it would seem advisable to keep the recorders aboard ship and have only the measuring elements in the water. The chief problems here are to obtain a rather high speed of thermal response and to keep the measuring element very small. The measuring elements would probably be used in gangs horizontally or vertically. It would seem that a speed of response of 1/10 second and a temperature sensitivity of .01°C are required. The 16 channel thermistor-recorder designed by NEL is fairly close to this but the time constants are too long to study very small scale turbulence.

b. An Instrument For Studying Micro Structure And The Isothermal Layer: This instrument should have similar characteristics to the above instrument except that it only needs one element and needs to go to depths of several hundred feet.

c. A Reliable BT To 1500 Meters To Study and Survey The Main Thermocline: This instrument should be continuously recording with a temperature precision of at least .03°C. It probably must be self-contained although an ability to record on deck via acoustic data transmission would be highly desirable. A resistance thermometer might well be the most satisfactory measuring element.

d. A Sensitive Recording BT To Study Temperature Structure Below The Thermocline: In order to determine the characteristic and origin of deep water, it is desirable to be able to find any discontinuities in the deep temperature structure.

e. Infra Red Instrument to Study Heat Flow Across The Surface: The possibility of using an infra red sensitive device to look for horizontal temperature gradients on the surface of the water is very interesting. Used either by aircraft, or from a ship's mast, such an instrument may be extremely useful to delineate current and eddy boundaries in a way which would be impossible by conventional means. In view of the large temperature differences found in the ocean, it would appear that many very interesting problems could be attacked with fairly simple equipment.

Devik has published some work on surface temperatures in Norwegian lakes measured by infra red pickups in recent years. While the state of the art of such devices is rather limited, it would seem that standard bolometer techniques would permit seeing temperature differentials of a degree or two.

f. A Long Period Temperature Recorder: Oceanography has not had the chance to study temperature records extending over a long period of time and hence we are uncertain about how rapidly major thermal changes take place. In particular we do not know how important large transients, such as eddies, influence the temperature. Klebba of Woods Hole has designed a recording thermometer which can record for a year but it has yet to be used over any extensive period at a critical location. In coastal areas it will probably be wiser to have the recorder operate over a shorter time. The sensitivities of such recorders should probably be from 0.1 to 0.01°C and the thermal stability must of course be excellent.

g. A Bottom Temperature Recorder: A bottom temperature recorder such as the one designed by Bullard and by Scripps should be made available so that problems in heat-flow out of the bottom can be studied.

h. Cheap BT For Harbor And Limnological Work: A cheap BT for harbor and limnological work should be made. This does not have to be used underway and the depth ranges need only be 100 feet. Here I would recommend a bellows type pressure element working against an extension spring. The thermometer should probably be bimetalic as it is cheap and almost foolproof and does not suffer from over-temperature. Recording should probably continue to be on a smoked glass slide although a waxed card might be satisfactory.

i. Instruments Which Give Density, Salinity Or A T-S Diagram: As long as we are interested in density and salinity there will always be a need for an instrument that records or indicates those values continuously. Although the basic components for such instruments have been used by many groups their assembly into a completed instrument has not been done very often and the resulting instruments were expensive and complicated. Much more needs to be done along these lines.

DISCUSSION: E.C. LaFond

With regard to Vine's statement of the temperature-measuring instruments needed I would like to emphasize the depth range required for measurements in the region of the Sofar sound channel. Since the axis varies in depth from around 150 meters to 1100 meters, the instrument should be capable of providing detailed temperature information down to 1200 or 1500 meters. Such information is important to the Navy Electronics Laboratory in the study of long-range transmission and sound intensities in the Sofar channel. The details from the surface to the axis are more important than those below the axis; the latter information can still be obtained by reversing thermometers. On long cruises in the Pacific, standard depths are not used at present for sampling water and temperature through the region of the sound-channel axis, instead, 50-meter intervals are used. If a new BT were developed to cover this depth range, it is believed that a temperature-salinity relation might be used in certain areas to obtain the sound velocity by measuring temperature alone.

Vine brought out the desirability of using an exponential depth scale to emphasize the surface layers. This has been discussed before, and there appear to be two ways of modifying a BT to give this changing scale in depth. One is to use tapered wire in making up the pressure coil, and the other is to make the diameter of the coil turns successively greater.

Vine also mentioned the processes in the sea in which we are interested. The needed information may be boiled down to actual temperatures or changes in temperature. More emphasis should be given instruments that measure changes in temperature with time, depth, and distance. An instrument which gives the difference, for example, between the temperature at the surface and at any depth does not require as great a range as the universal instrument which measures actual temperatures; it can thus achieve greater accuracy and is easier to use. For most purposes, this difference in temperature is sufficent.

The thermal sensing devices and recording methods will partly depend upon the specific problems at hand. For example, temperature instruments built and used at NEL for specific studies are a TPR -- temperature-profile-recorder, a 16-channel temperature recorder, and a CTD -- conductivity-temperature-depth indicator.

The TPR was required to measure accurately the heat capacity in lakes, since the BT was believed to get out of calibration occasionally, thus nullifying the study. The TPR is a portable unit consisting of a thermistor sensing element, 6-volt power supply, amplifier, and an Esterline Angus recorder. The recorder is geared to the drum containing an electrical cable to which the bead is fastened. When the bead is lowered in the water, the paper on the recorder is moved accordingly. Depth is measured by the length of wire paid out; therefore, the instrument is confined to shallow depths and wire angles of zero degrees in order to record depth properly. This instrument was used on the Lake Hefner water-loss investigation for fifteen months and then recalibrated with no apparent changes in calibration. A report on this instrument has appeared in Journal of Marine Research by Anderson (1951).

The 16-channel temperature recorder consists essentially of 16 TPR's feeding into a single temperature recorder. It requires 16 cables and 16 beads which can be spaced at any desired depth or horizontal distances up to 200 feet. The Brown recorder used has one indicator that automatically shifts from one channel to the next, printing an indication of the temperature for one bead after another. This instrument was required for the study of thermal-pockets and temperature variability in the Arctic and the central pacific.

The CTD was developed at NEL for the study of simultaneous temperature and salinity changes in regions of convergence and during advection processes in the Arctic. The temperature-sensing element in this instrument consisted of a group of ten 14B type thermistors. The response and accuracy of the temperature element was surprisingly good. However, the speed of the servo mechanism was a little slow; the speed has since been increased by the Oceanographic Department of the University of Wasington.

The problem of measuring temperatures in ice in the study of ice formation was also solved by thermistor beads mounted in plastic with leads extending through the ice to a junction box. A portable, heated power supply and galvanometer were taken to the site to make readings for temperature.

The list of recorders which are needed seems to have been adequately covered by Vine; however, there are a couple of points about uniformity and availability of instruments which should be emphasized. If various organizations could point out their needs for temperature-measuring equipment and agree on a few standard types, it would be possible to have these manufactured in quantity and even stock-piled for major operations. It may be possible to standardize on units of temperatures as well.

DISCUSSION: R.O. Reid

Surface layer - It might be well to expand upon the discussion of the surface layer as introduced by Vine. A knowledge of the fine structure in the layer of water immediately adjacent to the surface can be of great value in our understanding of boundary transfer processes. Existing instruments show essentially isothermal conditions in the water within mixed layers; however, knowledge of the detail near the surface is deficient. From physical considerations, if there is to be heat conducted to the surface to replenish that which is lost by back radiation and evaporation, one should expect to find a decrease in water temperature with approach to the surface. The development of micro-oceanographic gear would be of value in disclosing such gradients very near the surface, if they exist, and in procuring quantitative data on these gradients for use in surface heat budget studies. Such instruments would also be useful in ascertaining the pattern of surface or near surface temperatures which reflect perhaps the pattern of evaporative convection cells in the surface layer. Temperature inhomogeneities would be most pronounced at the surface where unstable conditions of density structure could exist in the presence of processes of cooling.

Thermal Response Factors - It has been stressed by Vine that short response time is essential in certain types of temperature measuring instruments in the sea. This is certainly true for any moving instrument, such as the BT, which is essentially a temperature change measuring device. However, instruments, such as the reversing thermometer, which have long response times are useful and essential if one wishes to eliminate the short term fluctuations of temperature. The aim of the hydrographic cast is to obtain representative distributions of temperature, and to subdue any erratic variations, of periods less than one-half minute. The roll of the ship, for instance, will cause temperature oscillations in the environment of the thermometer. Because of the slow response of the thermometer, however, these oscillations will be damped out.

Accuracy of Thermometric depths - The accuracy of the thermometric measurement of depth by means of the (U)-(P)* pair of thermometers is severely limited in the region of the thermocline by virture of the motion of the wire and/or internal waves. The presence of a temperature oscillation in the environment of the (U)-(P) pair, together with the fact that the structure of the (U) thermometer is such that its thermal response time is much smaller than that of the (P) thermometer, brings about errors in depths by virtue of the disparity of the thermal response components in the scale readings. This can partially be eliminated by using some sort of standardized pressure transmitting plug for the (U) thermometer which will bring its response time up to a value more nearly corresponding to that of the (P) thermometer.

Reliability of Reversing Thermometers - A system of classification of reversing thermometers derived from the history of the individual thermometers is useful in the processing of data. It has been found useful in the work of the Marine Life Research Program at the Scripps Institution of Oceanography, as well as in the Gulf Survey Program at Texas A.&M. to classify thermometers according to the percentages of failures (a record of which is made on the hydrographic data sheets). In addition, the statistics of the discrepancies in readings between two (P) thermometers placed on the same bottle is useful in assigning a reliability value to the thermometers.

DISCUSSION: Theodore R. Folsom**

The importance of new instruments to the advancement of science is often mentioned and theoretical and experimental problems involved during development are frequently stressed -- but it is seldom stressed that plain manufacturing difficulties frequently limit availability. It is true that sometimes a long wait is required before a valuable flash of design inspiration occurs -- but all difficulties do not then simply melt away. There follows a painful period of trial and test -- and a sometimes much more painful period when physical construction is carried out.

Many scientific instruments require craftsmanship of exceptional quality, a commodity not so abundant in recent years; but whether skilled or unskilled, present costs are extremely high. To minimize this ever-growing expense two expedients appear necessary; an increased investment must be made in production tools of the labor saving type, and a search and procurement organization must be set up so that maximum number of mass-produced components can be incorporated in the needed apparatus. Space for new machinery and for the search organization must be provided. The staff must increase and the shop facilities soon become so large that the institution is able to see that it has entered the manufacturing business.

---

* - (U) - unprotected; (P) - protected.

** - Dr. Folsom's discussion of Allyn Vine's paper has suggested to the editors a broad and important area not covered at the 1952 symposium -- the actual manufacture of research instruments, which is certainly a very large part of the whole instrument problem. The editors, therefore, have asked Dr. Folsom to generalize his original discussion with this point in mind. It is the editor's opinion that another meeting profitably could be devoted entirely to this subject.

Most research institutions long ago invested in elementary machine tools -- most of them soon found it necessary to separate maintenance shop facilities from instrument shops. Then the instrument shops in turn had to be expanded and subdivided; welding, drafting, and electrical operations required separate rooms. The expansion of instrument making facilities has followed a remarkably similar pattern in all academic research organizations.

Institutional instrument rooms often are beautiful to behold and appear to be models of efficient productivity. But the visiting V.I.P. is seldom told that down in the basement much of the equipment is duplicated for student use -- that institutional shops have very limited work-capacity -- and that whenever emergencies arrive the overload must be absorbed by resort to strenuous and generally inefficient measures.

Manufacturing inside the research institution is limited by several factors. The nature of the instrument and consequently its design and fabrication is unpredictable; thus it is not feasible to acquire all of the highly-specialized labor-saving tools that might be found occasionally useful. And it is impossible to retain on the shop staff a large number of specialists. As a result the standard, general purpose tools must be relied upon and the quantity of output can never hope to rise above a primitive level.

If the manufacture of instruments made within the institution is a limited and inefficient procedure, why is it attempted? This question comes up repeatedly. The general answer is that instrument development has proved most rapid and successful when the designer can be in close contact with the craftsmen who do the actual building. Maintenance of such facilities is admittedly expensive -- but on the other hand costs are likely to be even greater when the designer and the craftsman do not understand each other's problems thoroughly. This luxury cannot be carried to extremes, and opinion varies widely as to where the dividing line between formal and informal shop practices must be placed.

The internal shop facilities can no longer be more than token facilities, but it must not be forgotten that they contribute a most practical means for setting up contact with the outside manufacturing world. Interpretation and consultation regarding the technical merits of manufacturing proposals from the outside are commonly expected of the shop staff. The art of graphic specification -- drafting -- generally falls under the control of shop authority. It must be called upon when serious negotiations with outside factories are undertaken.

Just when outside agencies should be called in for duplicating or speeding up production of a well-developed apparatus is the subject of much discussion. Instruments are multifarious and diverse beyond all enumeration. It is not always possible to set up hard and fast rules so that a state of complete development can be recognized, and what might be a pilot-sized device in one field may be a production apparatus in another. The requirements for producing a few deep-sea coring tools may not be equivalent to those for many special hypodermic needles.

In certain instances outside manufacturing concerns become interested in the commercial possibilities of the instrument. This is rare, but it does happen. At this point the apparatus becomes an "invention", and takes on a mysterious character perhaps not originally associated with it. It is well that all concerned learn the legal rudiments of this situation. Although the institution and individual are not frequently rewarded, it is not uncommon for industrial concerns to proceed very slowly here. This points out that internal manufacture brings an often forgotten benefit -- privacy. And a whole lot can be said about the entirely different need for privacy in shops these days. Military security is now an additional instrument problem.

There seems to be little question but that the nucleus of an instrument factory must exist in a healthy research institution, but much of its value depends upon continued and skillful liaison with other agencies. It must maintain contact with industrial facilities, the shops of other research institutions, and the technological facilities of the government. And somehow it must learn to tolerate the learners, the graduate students, the workers in life-science departments. And somehow it must justify itself always with the bookkeepers who see the bills.

# GEOPHYSICAL MEASUREMENTS*

Russell W. Raitt

This report is restricted to the technique of seismic measurements made by the author in the Pacific Ocean. It is hoped that other participants in the symposium, having direct experience with seismic measurements in the Atlantic Ocean, gravity and magnetic observations, and geothermal gradient measurements, will contribute their knowledge of techniques used in these important fields.

The technique of seismic refraction measurements in the deep sea, thousands of miles from land, is strongly conditioned by two principal aspects: (1) all explosives must be carried from supply bases; (2) operating costs of long range, deep sea ships are high. Refraction profiles must be long in order to achieve penetration to the base of the earth's crust; they should be fired rapidly to avoid unnecessary loss of ship's time; the charges should be small to attain maximum use of the limited explosives capacity. Efforts to achieve these objectives have followed two lines of development:

1. Improvement of detectability of bottom refracted waves by reducing noise level, by filtering unwanted noise, by recording several hydrophones, and by proper choice of hydrophone depth.
2. Development of a simple, rapid, and reliable method of firing underway by dropping TNT bombs fused with slow-burning fuse cut to fire at desired depth.

Reduction of "dangling" noise at frequencies of the order of 10 cps was achieved by buoying hydrophones and the outer 50 foot of cable at neutral buoyancy. As the weak first arrivals at long range arrive nearly vertically, the optimum hydrophone depth is one quarter wave length of the dominant frequency of the refracted wave.

The Fourier spectrum of the explosive sound wave has a prominent peak at the "bubble pulse" frequency and falls off rapidly at lower frequencies. Maximum low frequency intensity of bottom refracted waves occurs at a shot depth of one quarter of the wave length of "bubble pulse" frequency. Optimum shot depths and frequencies according to this doctrine vary from 80 ft. and 15 cps for $\frac{1}{2}$ lbs. TNT to 205 ft. and 6 cps for 50 lbs. TNT.

Maximum range attained by this technique varies widely with sea conditions and bottom propagation. Under average conditions prevailing in the region of the northeast trade winds in the Pacific Ocean average maximum ranges are represented by the equation:

$$\Delta = 7W^{\frac{1}{2}}$$

---

* - Contribution No. 680 from the Scripps Institution of Oceanography.

where $\Delta$ is the range in km at which the bottom refracted wave becomes too weak to give a reliable first arrival, and W is the weight of TNT in lbs.

Seismic reflection studies have also been made, but have yielded useful results only when made in conjunction with refraction studies. Under favorable circumstances, reflections can be used to detect interfaces masked in refraction studies or for detailed mapping of interfaces identified in concurrent refraction profiles.

Before getting very far into the details of geophysical measurements it is worthwhile to examine their nature and how they differ, if any, from other types of measurements. I think it is fair to say that most geophysical measurements fall into the class of indirect measurements and by indirect measurements I mean measurements for which there is a large number of possible solutions. As an example of this type of measurement I like to consider the sonic depth finder, partly because it is not generally considered to yield an indirect measurement, and partly because it is a very widely used instrument. An echo sounder usually records the echo time from the nearest point on the bottom. In cases where the bottom is flat or very gently sloping this time can be used to determine the bottom depth beneath the ship provided the sonic velocity from surface to bottom is known. In cases where bottom slopes are steep and the topography irregular, the position from which the echo is returned is no longer directly beneath the ship and the depth is frequently indeterminate. For example, the great deeps of the world are found in narrow trenches and it may well be impossible to determine their greatest depth by sonic means.

This is illustrated by Figure 1. The upper part shows a profile of the bottom and the lower part shows the echogram of the apparent depth profile obtained by crossing the upper feature with an echo sounder. Some beautiful examples of similar features were described by Dr. Dietz and his colleagues. Under ideal circumstances, echoes can be resolved in the overlapping region in the center of the valley. Frequently, however, the second echo is obscured by the first one and the form of the bottom of the channel cannot be determined.

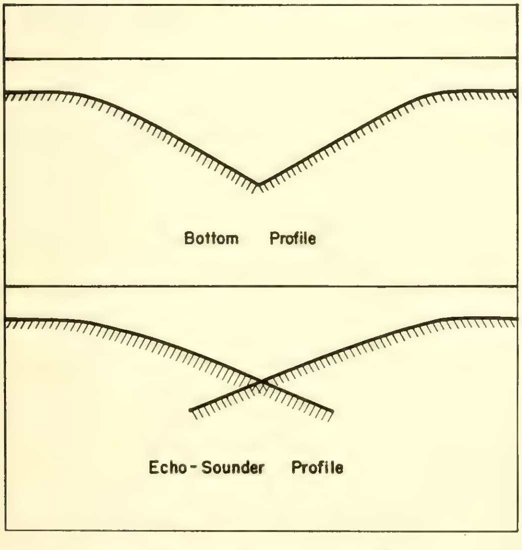


Fig. 1. Echogram of V-shaped bottom trench.

The degree of indeterminacy will vary considerably with the method of measurement and with the situation. In special cases, seismic refraction travel-time curves can be solved uniquely for seismic velocity as a function of depth. However, any set of surface gravity observations can be solved by an infinite set of possible density distribution within the surface. Most of these can be discarded as being unreasonable but some degree of indeterminacy will always remain.

The subject of geophysical measurements, if taken literally, is very broad, for geophysics is concerned with the physics of the atmosphere, hydrosphere, and lithosphere. As the first two of these areas are treated in other topics of this symposium, I think it is proper to limit this subject to what is generally known as solid earth geophysics, or the use of physics to obtain clues as to the nature of the earth's interior. Also, since we are concerned here with oceanographic instrumentation, it is further limited to the study of ocean bottom.

Owing to the relative inaccessibility of the ocean bottom as compared to the land surface, geophysics necessarily forms a more important function in the study of its nature. The principal methods used in this study have been the measurement of the magnetic and gravitational fields, the geothermal gradients in the sea bottom, and seismic measurements.

In interpretation of geophysical measurements it cannot be emphasized too strongly that the results generally yield merely clues of and not definite determinations of the nature of the earth's interior. For this reason a combination of several methods in the same region may yield a better solution than one of them alone. I will not attempt to discuss the details of the magnetic, gravity and geothermal measurements but will go directly to the subject with which I have had direct experience -- seismic refraction and reflection measurements in the Pacific Ocean. The discussants, Press and Worzel have had experience in these fields as well as seismic measurements in the Atlantic Ocean and I will not waste your time by discussing subjects which they can treat much better.

The kind of data obtained in seismic refraction measurements in the deep sea is shown in Figure 2 which illustrates the results for a receiving station a few hundred miles southeast of Hawaii. In the operation depicted, the receiving vessel, M/V HORIZON of the Scripps Institution of Oceanography, remained at rest while the firing ship, USS EPCE (R)857 of the U.S. Navy Electronics Laboratory dropped charges while approaching and receding from the HORIZON. In the upper part of the figure, three travel time distance curves are shown: (1) direct wave; (2) bottom reflection; (3) first arrival times of bottom refracted wave for each shot. The lower portion of the figure shows the bottom refracted travel times corrected for the time delay produced by the great thickness of water. The data of this lower graph are used to determine the velocities and thicknesses of the subbottom layers.

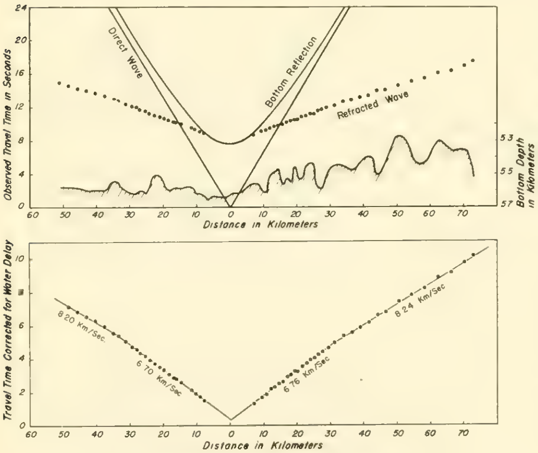


Fig. 2. Seismic refraction observations at a station southeast of Hawaii.

It is seen that a large number of charges are needed. At short range they must be closely spaced in order to detect breaks in slope caused by the lower velocity layers in the upper structure of the bottom. At greater range, where 8.2 km/sec velocity is observed, somewhat greater spacing can be used; but even here many shots are needed to determine the velocity and intercept with the desired accuracy. Because all charges must be carried thousands of miles from supply bases, maximum use of the explosive carrying capacity of the ships requires that utmost attention be given towards making the signal-to-noise ratio of the refracted waves as large as possible.

Efforts to achieve this at the Marine Physical Laboratory have been directed towards decreasing the background noise level and towards maximum utilization of explosive sound energy. Figure 3 illustrates the hydrophone arrangement which has been found most effective in reducing noise level. At the

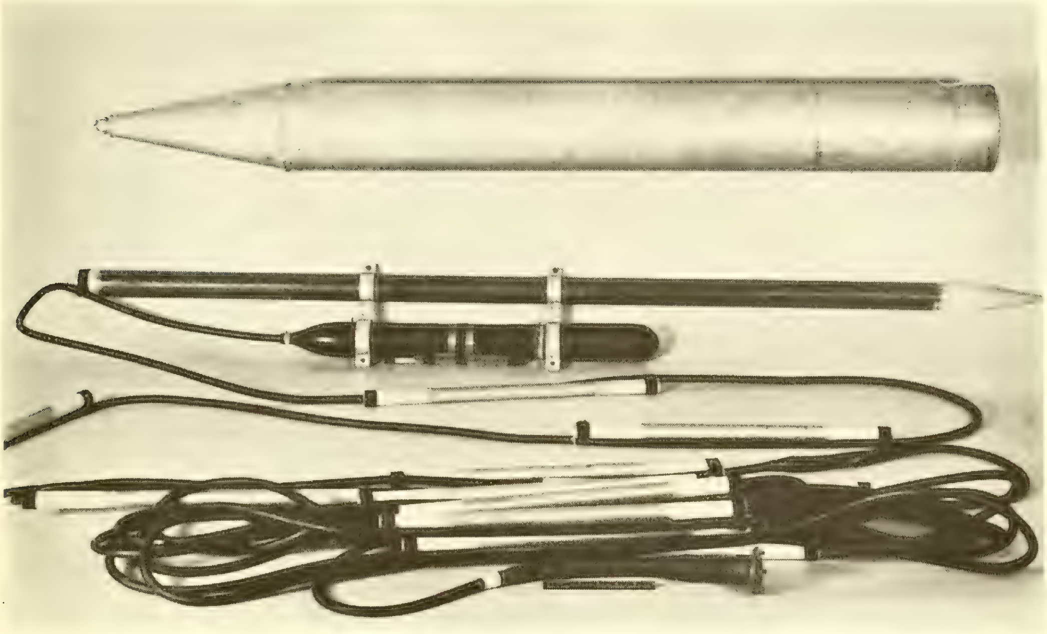


Fig. 3. Hydrophone suspension.

frequencies of the order of 10 cps used in seismic refraction work most of the noise is "dangling noise" produced by motion of the hydrophone and its suspension in the waves and currents. This is greatly reduced if the hydrophone and the outer 50 to 100 feet of line are buoyed to neutral buoyancy, as shown in Figure 3. This assembly then streams out from a weight suspended at the desired depth, with liberal use of rubber shock cord, from the spar buoy shown on the upper part of Figure 3. As the weak refracted waves at long range arrive nearly vertically, the optimum hydrophone depth is one quarter wave length of the dominant frequency. At this depth the surface reflected wave will be in phase with the direct wave.

The frequency spectrum of the refracted wave consists largely of low frequencies. At the scale of distances prevailing in deep sea observations, negligible energy above 50 cps is propagated through the bottom. Hence the problem of obtaining maximum utilization of explosive energy is to find the proper depth of shot and hydrophone at which the dominant low frequency of the explosion has maximum effects.

The only published work adequate for calculation of the energy spectrum of an explosion is the fine work of Arons and Yennie. Figure 4 shows the pressure-time curve as measured by them for a TNT explosion at 500 ft. depth in the sea. The distance in feet from the charge center was $W^{1/3}/0.352$ where W is the charge weight in lbs. The low frequency part of the fourier energy spectrum of this pressure time curve is shown in Figure 5. At frequencies up to 100 $\sec^{-1}\text{lb}^{1/3}$ the points are spaced closely enough to delineate a continuous curve. Above this frequency the points oscilate rapidly, and are sensitive to errors in the pressure time curve. In this region the dashed curve represents the average level. At frequencies above 2000 $\sec^{-1}\text{lb}^{1/3}$ most of the sound energy resides in the initial sharp pressure pulse whose form can be approximated

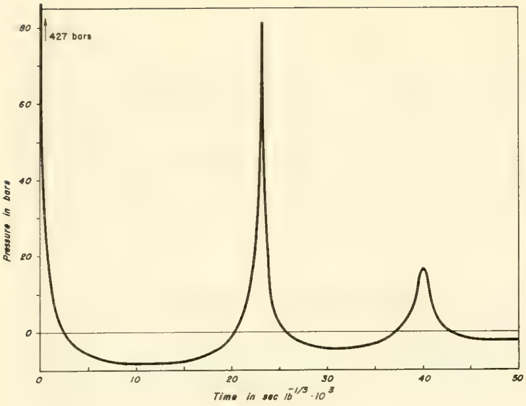


Fig. 4. Pressure-time curve of a TNT explosion at 500 feet depth.

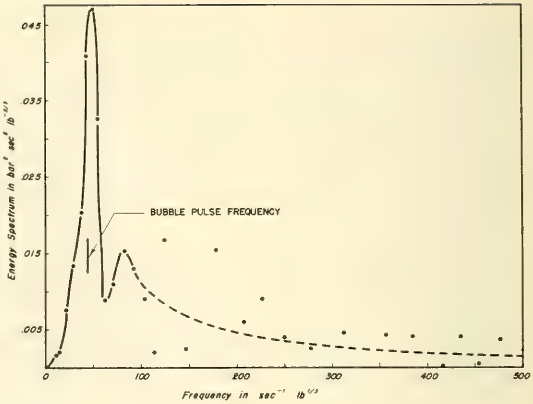


Fig. 5. Low-frequency part of the Fourier energy spectrum of an explosion at 500 feet depth.

by $p = P_o e^{-at}$ and whose energy spectrum is given by $P_o^2/(a^2 + W^2)$, where W is the angular frequency in radians per second.

Figure 6 shows the complete energy spectrum expressed logarithmically to encompass the great range of energy and frequency. The two solid parts of the curve represent calculated portions. The dashed central part is the estimated average of the irregular oscillating part. Figure 7 gives the cumulative energy spectrum, i.e., the total integrated energy in all frequencies below the frequency shown in the abscissae.

From Figures 5, 6, and 7 it can be seen that the most prominent feature of the spectrum is a peak at a frequency approximately equal to the reciprocal of the interval between the initial pressure pulse and the first bubble pulse. This is called the bubble-pulse frequency. Approximately one-fifth of the total radiated sound energy is contained in this peak. Although pressure-time curves for depths other than 500 feet are unavailable, and hence the energy spectra are unknown, it appears reasonable to assume that the low frequency peak will occur at bubble pulse frequency for all charge depths.

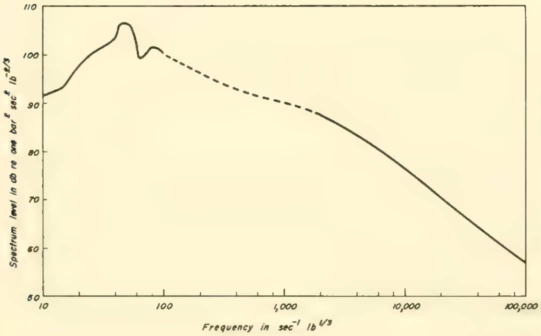


Fig. 6. Complete Fourier energy spectrum.

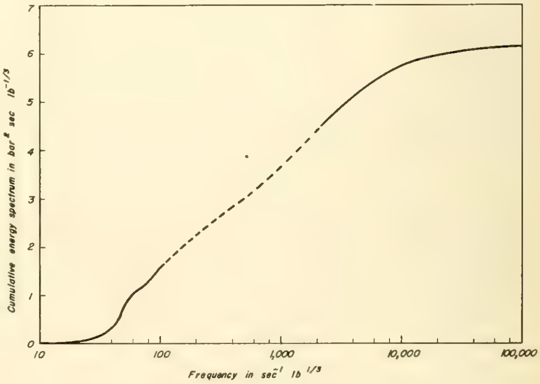


Fig. 7. Cumulative energy spectrum.

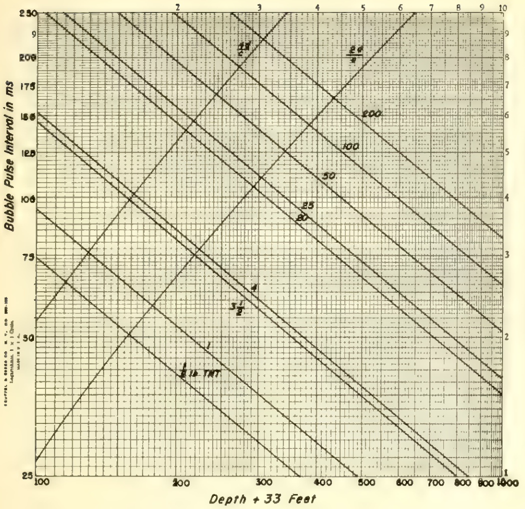


Fig. 8. Dependence of bubble-pulse frequency.

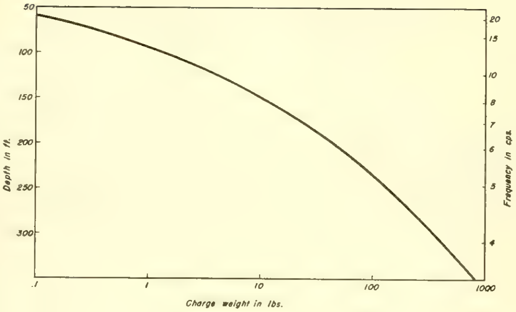


Fig. 9. Optimum charge depth as a function of charge weight.

Figure 8 shows the dependence of bubble pulse interval on depth for various sizes of TNT charges. The two curves labeled 4d/c and 2d/c represent twice the time and the time, respectively required for the sound to travel vertically to the surface and back to charge depth. Hence the intersections of the upper curve of Figure 8 with the bubble pulse curves determine the depths at which the reflected sound of bubble pulse frequency is in phase with the direct sound sent vertically downward. They define a relation between charge weight and the depth at which maximum energy of bubble pulse frequency is directed downwards. It is the depth to one-quarter wave level of bubble pulse frequency.

Figure 9 shows a plot of this depth for TNT charges from 0.1 lb. to 1000 lb. On the right side of the graph are shown the bubble pulse frequencies corresponding to the plotted depths. For the charge sizes of $\frac{1}{2}$ to 100 lbs. used in seismic refraction work, the depths and frequencies vary from 80 to 235 feet and from 15 to 5 cps. Examples of the refracted waves obtained by this shooting doctrine are shown in Figure 10 which depicts two pairs of records made at the ranges at which the charge weight was changed from 4 to 50 lbs. The frequencies are roughly 10 and 6 cps, respectively, in agreement with the graph in Figure 9.

In order to eliminate undesired sounds outside the frequency range of the refracted waves, the bottom re-

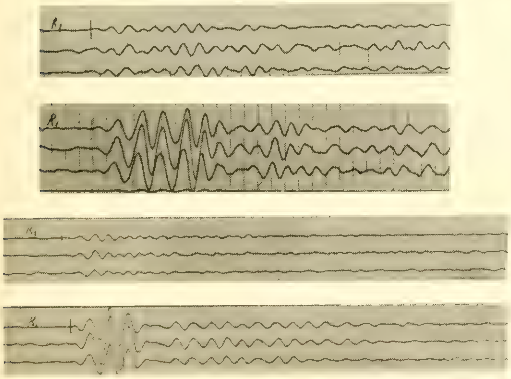


Fig. 10. Effect of increasing charge weight from 4 to 50 lbs. In each of the two pairs of oscillograms the upper one represents a 4 lb. charge and the lower one a 50 lb. charge. The distances are approximately 25 km.

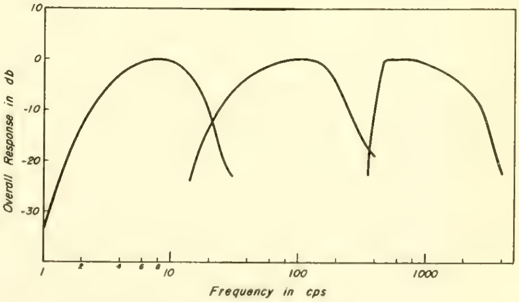


Fig. 11. Frequency response of recording system.

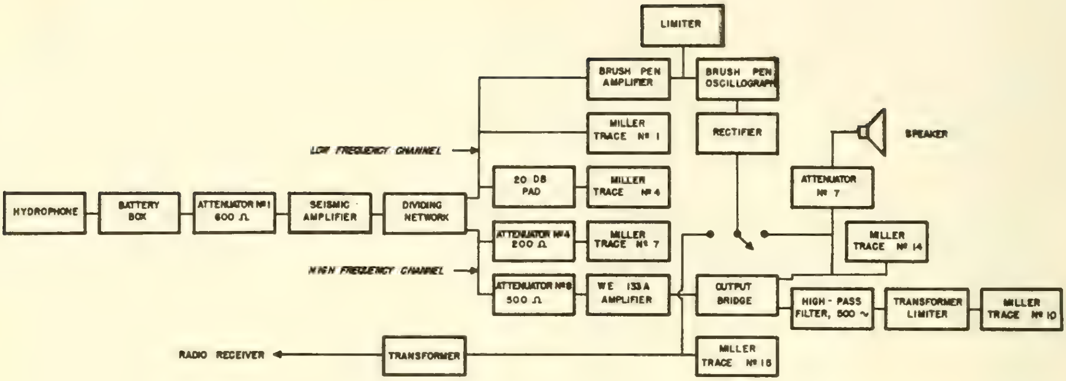
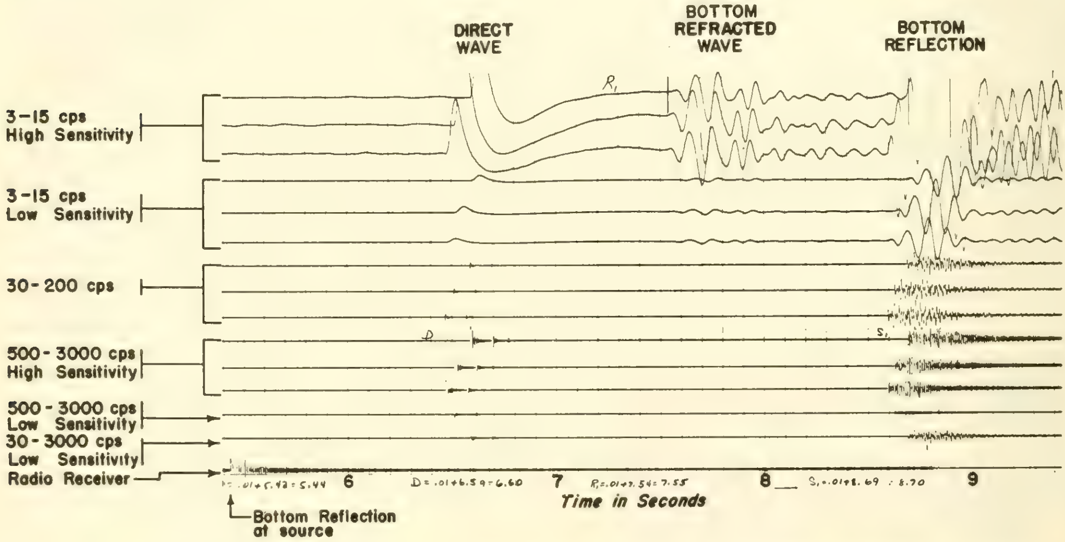

LIMITER
BRUSH PEN AMPLIFIER
BRUSH PEN OSCILLOGRAPH
MILLER TRACE № 1
RECTIFIER
SPEAKER
LOW FREQUENCY CHANNEL
20 DB PAD
MILLER TRACE № 4
ATTENUATOR № 7
HYDROPHONE
BATTERY BOX
ATTENUATOR № 1 600 Ω
SEISMIC AMPLIFIER
DIVIDING NETWORK
ATTENUATOR № 4 200 Ω
MILLER TRACE № 7
MILLER TRACE № 14
HIGH FREQUENCY CHANNEL
ATTENUATOR № 8 500 Ω
WE 133A AMPLIFIER
OUTPUT BRIDGE
HIGH - PASS FILTER, 500 ~
TRANSFORMER LIMITER
MILLER TRACE № 10
RADIO RECEIVER
TRANSFORMER
MILLER TRACE № 15

Fig. 12. Block diagram of recording system.

fracted waves are recorded on a low frequency channel which eliminates the "dangling noise" below 3 cps and the ship noise above 20 cps. The water-borne sounds used in determining the shot-hydrophone distances are recorded on wide bands roughly centered at 100 cps and 1000 cps respectively. The response of the three bands to a constant pressure input to the hydrophone is shown in Figure 11.



**OSCILLOGRAM OF EXPLOSIVE WAVES USED IN SEISMIC STUDIES**

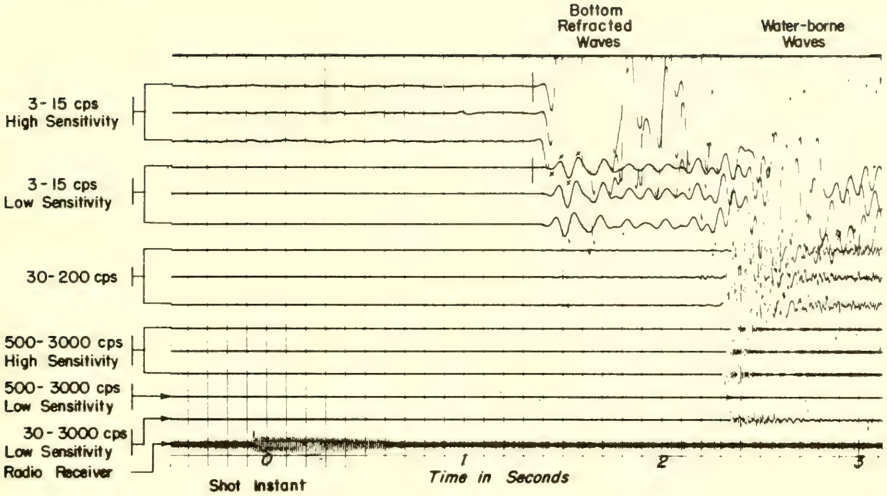
**Length of three-hydrophone spread -- 600 feet.**

**Charge -- $3\frac{1}{2}$ lbs. TNT.**

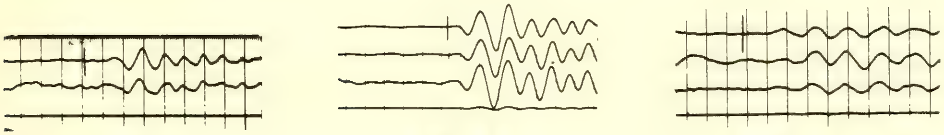
**Shot Distance -- 5.5 nautical miles**

**Ocean Depth -- 2255 fathoms**

Fig. 13. Sample oscillogram of a seismic refraction shot in deep water.



COMPLETE RECORD OF A 1-LB CHARGE, 4.0 KM DISTANCE
Bikini Lagoon


4 lbs, 34.6 km
Bikini Lagoon

20 lbs, 22.8 km
SW of Station K'

50 lbs, 61.0 km
NW of Station J
Deep Water

LOW FREQUENCY CHANNELS ONLY

Fig. 14. Sample oscillogram of seismic refraction shots in Bikini Lagoon and in deep water outside Bikini Atoll.

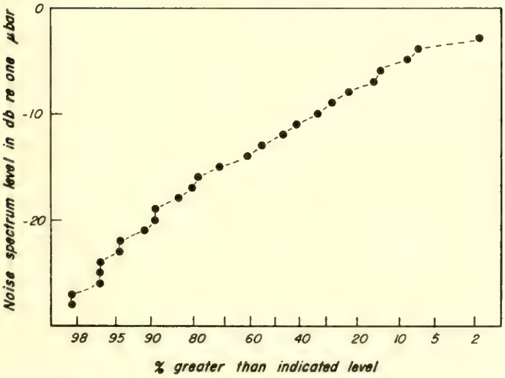


Fig. 15. Cumulative distribution of low-frequency noise spectrum levels observed in the North Equatorial Pacific.

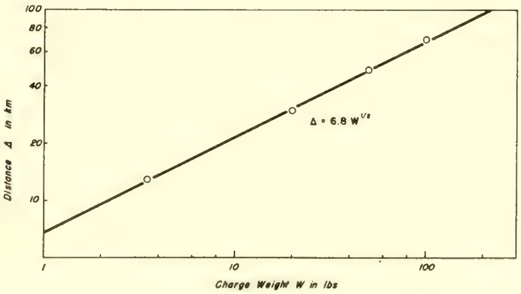


Fig. 16. Maximum range of detection of beginning of the bottom refracted wave, as a function of charge weight.

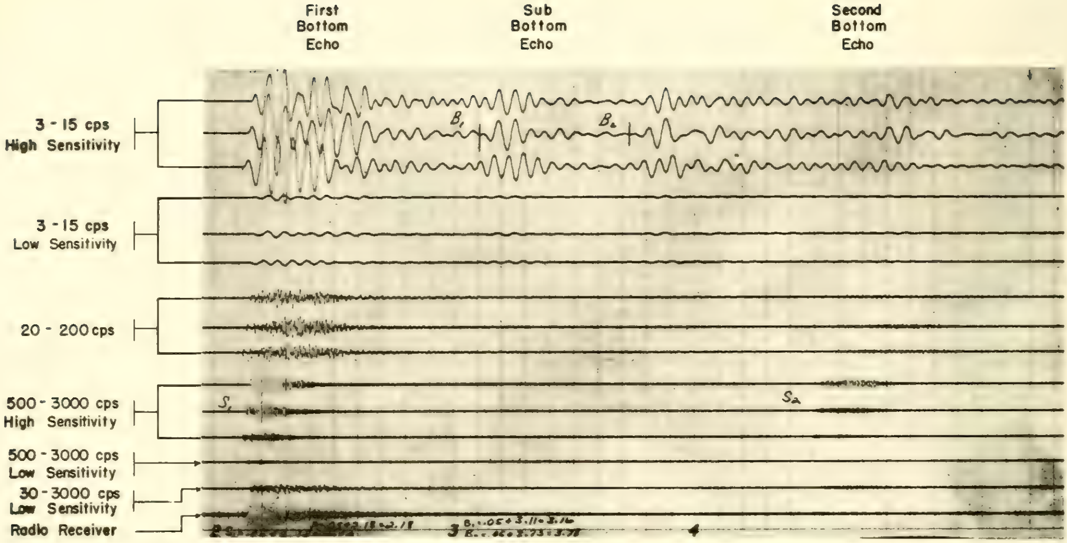


Fig. 17. Oscillogram of Bottom Echo in San Nicolas Basin.

Figure 12 illustrates a block diagram of the various elements used in recording the output of one hydrophone channel. The principal record is made on a 15-channel Miller oscillograph recording on photographic paper 6 inches wide. A Brush pen oscillograph is also used to monitor the record. Two other hydrophones record the three frequency bands on the Miller oscillograph but are unmonitored by the Brush oscillograph. Figures 13 and 14 are examples of records made in deep water and shallow water respectively.

The performance of seismic refraction equipment is best evaluated in terms of the maximum range at which the beginning of the bottom refracted wave can be determined with reasonable reliability. This range is quite variable because of the variability of the intensity of the refracted waves but even more because of the variability of noise levels. Figure 15, which shows a cumulative distribution of the spectrum levels observed on the low frequency channel on the 1950 expedition to the Mid-Pacific. Each point represents the average of 20 to 30 measurements at a single station, so the variations are systematic changes due to day-to-day changes of conditions, and represent a cross section of observations in the North Equatorial Pacific, where the trade winds commonly have a strength of Beaufort 4.

Maximum ranges obtained under these conditions are plotted as a function of charge weight in Figure 16. The straight line through the points has the equation $\Delta = 6.8W^{\frac{1}{2}}$, where $\Delta$ is the range in kilometers and W is the weight of TNT in lbs.

Under proper conditions seismic reflection measurements can give useful information about the subsurface. An example is shown in Figure 17 which shows an oscillogram of a bottom echo obtained in San Nicholas Basin about 80 miles west of San Diego. In this area the bottom is flat, hence there are no confusing echoes from hills and valleys, such as are frequently observed in rough topography. Two sub-bottom echoes, $B_1$ and $B_2$, are observed on the low frequency channels, but not on the higher frequency channels. Evidently the echoes are caused by a gradual change of elastic properties, rather than an abrupt transition. Hence the long waves received by the low frequency channel are strongly reflected while higher frequencies are not. This demonstrates that frequency selectivity is useful for "tuning in" the important sub-bottom echoes.

Even when bottom echoes are of the comparatively high quality illustrated in Figure 17 they do not yield directly very much information about the nature of the reflecting interfaces. However, when combined with refraction measurements in the area, velocities can be measured, depths calculated and strata roughly identified. Reflections may then be used to supply detailed information about variation in depth to the important interfaces.

DISCUSSION: Frank Press

Dr. Raitt's complete discussion of seismic refraction measurements requires very little additional comment. The instrumentation and techniques developed at Scripps Oceanographic Institution closely parallels that evolved by the Columbia University -- Woods Hole groups. It has been the experience of both groups that an outstanding problem still remains to be solved -- the reduction of noise associated with the motion of the hydrophone through the water.

Accumulation of seismic refraction data for the ocean floor is now proceeding at a rapid pace. Most of the measurements consist of isolated reversed profiles or several profiles along a line. This reconnaissance technique serves to point out the major features of suboceanic crustal structure. Thought should now be given to the use of continuous profiling methods over distances of the dimensions of ocean basins. Only in this way can the details of ocean bottom structure be mapped. Some of the most significant contributions using seismic measurements will be made from investigations of the key structures of the ocean floor -- continental margins, deep sea trenches, submarine mountain areas. A major problem facing these studies is the determination of a proper topographic correction to be applied to refraction data obtained over rough bottom. Certainly detailed fathograms and a multiplicity of shots in the first few miles of the profile will be required.

Continuous reflection shooting should be made part of every cruise since negligible ships time is required and data essential to proper understanding of refraction results and sedimentation studies will be obtained. Deep sea reflection techniques at this present stage of development are crude compared to methods developed by petroleum geophysicists for use in shallow water. There is room for much improvement here.

A detailed evaluation of the British technique of making refraction measurements from a single vessel using telemetering detectors should be made. Although some of the obvious disadvantages such as limited profile length and increased time are immediately evident, the tremendous saving in cost and the more frequent availability of a single ship is a major factor in its favor as an alternative method.

One does not ordinarily think of a seismograph as an oceanographic instrument. Significant information has been obtained, however, by seismographs placed on oceanic islands. These observations supplement the point by point seismic refraction measurements by data averaging conditions over long distances. A minimum installation on an island should include a short period, vertical component seismograph with peak response between 1/5 and 1 second and three matched, long period component seismographs. A particularly useful instrument consists of a 10-20 second pendulum operating into a 90 second galvanometer; the resulting period response minimizes the effect of microseisms which occur with particularly large amplitudes on islands. Consideration should be given to installation of such seismograph stations on key islands, the cost of a single station being no more than that of maintaining an oceanographic vessel for a few days.

Existing Sofar installations have been used to monitor tectonic activity of the sea floor as manifest by the occurrence of T-Phases (sounds originating in earthquakes and propagated through the Sofar channel). Occasionally the compressional and shear wave phases have been recorded. Much additional information on sound propagation in the ocean and crustal structure of the ocean floor could be obtained by Sofar detectors having frequency response down to 1 cycle per second. Even with present Sofar installations, seismicity of the ocean floor can be determined with a degree of precision previously not possible. Topographic reflections of T-Phases have been used to delineate unknown features of sea floor topography.

The processes of interaction between the atmosphere and the oceans which produce microseisms, air-coupled tidal waves, tidal waves associated with severe storms is a fertile field for investigation. Necessary instrumentation includes seismographs described previously, a sensitive microbarovariograph such as developed at Columbia University, tsunami recorders as developed at Scripps Oceanographic Institution and standard tide gauges. A deep sea pressure recorder sensitive to fluctuations with microseism periods is particularly desirable.

DISCUSSION: J. Lamar Worzel

Since Dr. Raitt has described the methods and equipment for making seismic measurements at sea, which are similar to those we have evolved on the Atlantic side during the past 16 years, and Dr. Press has described the earthquake seismology studies and equipment in use at the Lamont Geological Observatory, my comments will be restricted to some of the other phases of geophysics that bear on oceanography.

Soundings are of importance in themselves for topographic studies, but they are of great significance in conjunction with nearly every other geophysical observation. For almost all purposes a recording of the soundings is vastly superior to a visual or audible presentation. Until recently sounders available in this country could only record on the 0 to 2000 fathom scale. Fortunately, many of us have learned to make a simple modification to these recorders so that they will also record on the 2000 to 4000 fathom scale, so that they can now be used over about 80% more of the oceanic areas. These modified sounders have proved useful but a number of additions or changes are needed to make them really adequate for taking proper sounding data for research purposes. First of all, a controlled frequency for driving the timing motor is essential. The sounding measurement is only as good as the timing measurement. Secondly, the pit log readings and time should be automatically put on the record at intervals of about one-half hour. Many sounding records have been useless because they could not be related to the ships track. At present a 24 hour watch must be employed for this purpose, and man hours at sea are especially expensive. Thirdly, the resolution is not adequate for many problems. It should be possible to expand the scale so that full scale covers at least 200 fathoms at any part of the range from 0 to 4000 fathoms. We have become convinced that many of the plains we find in the Atlantic have slopes, perhaps as small as .05 ft/mile. Fourthly, the reliability and repair procedures must be greatly improved. Many miles of sounding track have been lost while a trained technician was repairing the sounder and many more miles of sounding track have been lost for the lack of a trained technician to make repairs at sea.

Another geophysical measurement made at sea, of great importance, is the measurement of gravity. Since there is no known variation of gravity with time, measurements at the same location only have to be made as cross checks on the apparatus. At present, the only apparatus capable of measuring gravity at sea is the Vening-Meinesz (1929) pendulum apparatus. The measurements must be made from a submerged submarine to avoid the grosser effects of the acceleration due to surface wave motion. This gear is accurate to ±3 milligals (±.003 cm/sec$^2$). Many improvements in this apparatus have been made principally to simplify its operation, adjustment, and data reductions, (Worzel and Ewing, 1947, 1948, 1949) and two major improvements have been made. These major improvements are the use of a crystal chronometer for time measurements to replace the spring wound chronometers, (Ewing 1937) and the long period pendulum apparatus (Vening-Meinesz, 1941) necessary to measure the second order corrections, whose importance was first pointed out by Browne (1937).

In the computations it is necessary to make corrections for pendulum amplitude, air density, temperature, isochronism of the pendulums which constitue a fictitious pendulum, chronometer rate, deviation of the pendulum swinging plane from the vertical, second order corrections for horizontal and vertical accelerations, the depth of the submarine, and the Eotvos correction (east-west component of velocity during the observation). For topographic and isostatic reductions the water depth is also required.

While it is of course desirable to have air-borne gravimeters or surface ship borne or towed gravimeters, it is unlikely that either will be forthcoming in the near future due to the very large acceleration to which surface ships and aircraft are subject. It is possible that a gravimeter for use on submarines will will be forthcoming in the not too distance future. Such an instrument cannot be expected to cut down the observing time much below the present 25 minutes, especially if we strive for 1 milligal accuracy, since 1 milligal vertical acceleration continued over a period of time of the order of 10 minutes would just produce an observable depth change in the presence of surface waves. Such an instrument would shorten the time to reduce the gravity value, now 4 hours (1 hour for photographic processing, 3 hours for record reading and computing) to about 5 minutes.

Gravity observations and their associated measurements are of importance to oceanography to determine the density distributions in the crust beneath the ocean, and for the observations of the wave motions in deep water. It would be possible to use the Eotvos effect to determine the East-West current velocity.

For geophysical purposes existing airborne total field magnetometers are satisfactory (Wyckoff, 1948) (Frowe, 1948). However, since airplanes seldom know where they are at sea to better than 15 or 20 miles, it is also important to have a ship towed magnetometer to determine the relationship of magnetic anomalies to the bottom topography, as a means of interpreting the airborne data. We have made an adaptation of one of the airborne instruments for this purpose. Since this merely involves replacing the "bird" with a watertight "fish", no instrumentation details need be given. The biggest problem, now well on the way to its solution, has been that of obtaining a cable able to withstand the strain of towing for thousands of miles in all kinds of weather.

The only magnetic instrumentation that is needed is an airborne or seaborne instrument capable of measuring the necessary three components required to describe adequately the earth's magnetic field at a point. This instrument would make it possible to observe the areal distribution of the earth's magnetic field in detail for the first time.

A new method known as the Carbon-14 method of measuring some of the ocean currents has evolved. The principle of the method is to measure the decay of radioactive carbon in a water sample. The amount of decay is a measure of the number of years since the water has been in contact with the atmosphere. For the measuring purposes it is necessary to obtain a 300 gallon sample from which a 12 gram sample of carbon can be extracted. The carbon is obtained by processing the water sample with concentrated sulphuric acid, bubbling $CO_2$-free nitrogen through the sample to drive off the $CO_2$ gas and collecting the $CO_2$ in ascarite after passing the gas through a suitable drying agent. The ascarite is sealed and returned to the counting laboratory where the remainder of the processing and counting is completed (Kulp, 1952).

Originally the 300 gallon samples were taken with rigid steel tanks about 4 ft. in diameter and 5 ft. tall with ports at both ends. Recently a sampler about $1\frac{1}{2}$ ft. in diameter and 12 ft. long has been developed. This sampler is made of canvas so that the tube can be collapsed, and a single port at the top end is provided. The sampler is sent down into the water collapsed. When recovery of the sampler is commenced, a propeller, which can only operate when in upward motion, first releases the bag and about 30 seconds later releases the port cover. At the surface, the water is pumped from the bag into a processing tank on the deck of the ship. The processing, which formerly required four hours, can now be completed in 10 to 15 minutes. Since the canvas samplers are light and have small cross-sectional areas, multiple casts are completely practical.

Two water samples from about latitude 55°N and close to the mid-Atlantic ridge have given water ages of about 1700 years. Although more measurements are required, these indicate that oceanic circulation is much slower than most workers have believed. If the water is moving along the bottom, requiring centuries to move from the poles to the equator, the heat flow through the ocean floor must be negligible and the whole heat budget of the earth will require reconsideration.

The only instrumentation improvement which appears desirable is a pressure indicator to confirm the depth at which the port closure occurred. Alternatively a technique for removing the carbon in situ would eliminate all questions of contamination and would greatly simplify the handling problems.

Recordings of sounds from large charges fired in the Sofar channel have revealed numerous topographic echoes in the Atlantic (Luskin, in press). About 20 echoes have been identified with known sea mounts, islands, or shore lines. The echoes from shore lines arrive as a sequence of discrete echoes rather than a long continuous echo. The position of a new sea mount about 350 miles from Bermuda was forecast on the basis of its echoes, and a subsequent cruise confirmed its existence within about 5 miles of the predicted position. No echoes of measurable amplitude have been found which do not conform to known obstructions. No instrumentation is required for this work which is not a normal component of a Sofar station. For best results the explosion should occur at the sound channel axis and should be of 50 lbs. or more of TNT. Such charges can readily be made from standard charges utilizing Woods Hole detonators.

## REFLRENCES: R. Raitt

ARONS, A.B., and YENNIE, D.R. "Energy Partition in Underwater Explosion Phenomena". *Rev. Mod. Phys. 20, pp. 519-536, July 1948.*

## REFERENCES: J. Worzel

BROWNE, B.C. 1937. "The Measurement of Gravity at Sea". *Mon. Not. Roy. Astr. Soc. Geophys. Suppl. Vol. 4, pp. 271-279.*

EWING, MAURICE. 1937. "Gravity Measurements on the U.S.S.Barracuda". *Trans. Am. Geophys. Un. Part I, pp. 66-69.*

FROWE, EUGENE. 1948. "A Total Field Magnetometer for Mobile Operation". *Geophysics. Vol. 13, no. 2, pp. 209-215.*

KULP, J. LAURENCE, TRYON, LANSING E. and FEELY, HERBERT W. 1952. "Techniques of Natural Carbon-14 Determination". *Trans. Am. Geophys. Un. Vol. 33, no. 2, pp. 183-192.*

LUSKIN, BERNARD, LANDISMAN, MARK, TIREY, GEORGE B., and HAMILTON, G.R. "Submarine Topographic Echoes from Explosive Sound". *Bull. Geol. Soc. Am. Vol. 63, no. 10, pp. 1053-1068.*

VENING-MEINESZ, F.A. 1929. "Theory and Practice of Pendulum Observations at Sea". *J. Waltman, Jr., Delft.*

VENING-MEINESZ, F.A. 1941. "Theory and Practice of Pendulum Observations at Sea". *Part II, J. Waltman, Jr., Delft.*

WORZEL, J. LAMAR, and EWING, MAURICE. 1950. "Gravity Measurements at Sea". 1947. *Trans. Am. Geophys. Un. Vol. 31, no. 6, pp. 917-923.*

WORZEL, J. LAMAR, and EWING, MAURICE. 1952. "Gravity Measurement at Sea, 1948 and 1949". *Trans. Am. Geophys. Un. Vol. 33, no. 3, pp. 453-460.*

WYCKOFF, RALPH D. 1948. "The Gulf Airborne Magnetometic". *Geophysics, Vol. 13, No. 2, p. 182-209.*

## REFERENCES: F. Press

BROWNE, B.C. "The Measurement of Gravity at Sea". *Geophys. Supplement of the Monthly Notices of thr R.A.S., Vol. 4, p. 271-279, Sept. 1937.*

EWING, MAURICE, "Gravity Measurements on the U.S.S.Barracuda". *Trans. Am. Geophys. Union, Part 1, p. 66-69, 1937.*

## REFERENCES: F. Press

KULP, J. LAURENCE, TRYON, LANSING E., and FEELY, HERBERT W. "Techniques of Natural Carbon-14 Determination". *Trans. Am. Geophys. Union, V. 33, No. 2, p. 183-192, April 1952.*

LUSKIN, BERNARD, LANDISMAN, MARK, TIREY, GEORGE B., and HAMILTON. "Submarine Echoes from Explosive Sound". *Bull. Seol. Soc. of Am. in press.*

TROWE, EUGENE. "A Total Field Magnetometer for Mobile Operation". *Geophysics, V. 13, No. 2, p. 209-215, April 1948.*

VENING-MEINESZ, F.A. "Theory and Practice of Pendulum Observations at Sea". *J. Waltman, Jr. - Delft, 1929.*

VENING-MEINESZ, F.A. "Theory and Practice of Pendulum Observatiors at Sea". *Part II, Waltman, Delft, 1941.*

WORZEL, J. LAMAR, and EWING, MAURICE. "Gravity Measurements at Sea". *Trans. Am. Geophys. Union, v. 31, No. 6, p. 917-923, December 1950.*

WORZEL, J. LAMAR, and EWING, MAURICE. "Gravity Measurements at Sea". *1948, 1948, Trans. Am. Geophys. Union, v. 33, No. 3, p. 453-460, June 1952.*

WYCKOFF, R.D. "The Gulf Airborne Magnetometer". *Geophys, v. 13, No.2, p. 182-209, April 1948.*

# SEA ICE PROBLEMS

Clifford A. Barnes

## INTRODUCTION

In dealing with sea ice, oceanographers are concerned primarily with properties, processes and distribution. The properties may be physical, such as acoustic, electromagnetic, optical, hardness, strength, crystal structure and the like, chemical or geological. Processes include the interaction with water, the atmosphere, other ice and the bottom or coast, freezing and melting, disintegration and movement. The distribution involves arrangement, compactness of cover, thickness, size, and surface and subsurface characteristics, all of which change in space and time, necessitating both synoptic and climatic geographic pictures.

The term "sea ice" is used herein to refer to any ice formed by the freezing of sea water. Glacial ice formed on land, and river and lake ice discharge into the sea in considerable amount. These ice types may drift great distances at sea, but differ from true sea ice. In investigating the physical properties of the different ice types and the response of ice to the oceanographic and meteorological environment, much of the basic instrumentation is independent of the ice type. The drift rates of pack ice or of berg fragments before the wind for example depends largely on the size, shape, orientation and grouping of the individual pieces and little upon the chemical composition of the ice. On the other hand, sea ice is unique in being formed in saline solution and entrapping appreciable amounts of salt. Investigating such problems as the freshening of ice on aging, or the changing of ion-ratios within the ice may require very specialized instrumentation.

Some question may be raised concerning the extent to which oceanography is involved in sea ice studies, and to what extent the instrumentation used falls into the category of oceanographic instrumentation. The formation, movement, disintegration and many of the physical properties of sea ice are intimately related to conditions in the sea and lower atmosphere and involve particularly the fields of oceanography and meteorology. Currents and the physical and chemical properties of the water mass limit the distribution of sea ice. These oceanographic conditions are more or less directly influenced by the meteorological conditions. The temperature regime within sea ice and its thermal conductivity may be almost exclusively a problem in physics, the structure of the ice crystals one in geology, and the precipitation of salts during the freezing process one in chemistry. In experimental work, the same instrumentation might well be used regardless of whether or not the attack is primarily oceanographic. Oceanographers have always borrowed heavily from the contributing or related sciences and have done so in the case of instrumentation for sea ice studies. Most of the instruments used have been developed for other purposes and adapted to sea ice studies, specialized instrumentation being held to a minimum. At the current level of sea ice studies, this trend of adapting or modifying existing equipment will probably continue for some years.

Many recent advances in the knowledge of sea ice have been afforded through better facilities such as heavy icebreakers, long-range reconnaissance planes, and Arctic stations. These facilities and the electronic navigational gear for defining position or locating targets can hardly be called oceanographic instruments. No discussion of sea ice instrumentation, however, would be complete without considering them. Other recent aids in studying sea ice include attempts to standardize ice terminology, long provincial, so that the different ice observers will understand each other. The ice glossary, ice atlas, ice reporting forms and instructions for ice observers published by the Hydrographic Office should promote better ice observations and facilitate interpreting the observations.

In the following paragraphs, an attempt is made briefly to outline sea ice problems and attendant instrumentation. It is recognized that the listing will have many large gaps. It is hoped, however, that it will serve as a starting point for the various commentators to add new material and present new viewpoints.

## FACILITIES FOR SEA ICE STUDIES

In only limited areas of navigational importance has sea ice received much attention in the past. These, in general, are the fringe areas containing important commercial ports, or those lying on direct access routes thereto, which at times may be ice blocked. An outstanding example is the Gulf of St. Lawrence area in which ice of the gulf and river for about five months each winter blocks access to Montreal, eastern Canada's largest seaport. Eastward on the Grand Bank of Newfoundland, sea ice and icebergs have caused shipping to detour far to the south in the spring. Although icebergs here have caused notable marine disasters, the sea ice has been the real barrier to navigation. Lands along the periphery of the Arctic Ocean and to quite low latitudes on the western sides of the Atlantic and Pacific are ice blocked for periods of a few months to twelve months each year. In some areas, the annual shipping needs must be satisfied in a brief summer period. In others, commercial exploitation may await better transportation facilities. The exploration of the Arctic Basin proper and the pack ice area surrounding the Antarctic has been carried out on a relatively few isolated expeditions. No comprehensive synoptic surveys have been made and the climatic picture of ice conditions is based on sporadic observations. A big obstacle in obtaining this information has been the lack of suitable facilities to provide the investigator adequate contact with ice areas. These facilities include surface vessels, submarines, aircraft of various types, and suitably located stations based on shore or on the ice itself.

Surface Vessels - The first surface vessel built specifically to explore the depths of the Arctic, and succeeding in doing so, was the FRAM under Fridtjof Nansen (Nansen, 1897) in the years 1893 to 1896. The FRAM was a wooden vessel of 402 gross tons, 128 feet over-all length, 36 feet extreme breadth and 17 feet depth. It was schooner rigged and powered with a 220 h.p. triple expansion steam engine. Once frozen in the Arctic pack, it was carried along by the ice until its release by natural discharge of the ice from the periphery. Prior to the FRAM, whalers and others had contributed much general knowledge of the fringe areas of the Arctic. Subsequent to Nansen's expedition, improved and more powerful icebreakers have been made, notably by the United States and Russia. These modern breakers are still at the mercy of the pack ice in winter. For example, the Russian SEDOV expedition (Zubov, 1940) covered much the same area as the FRAM and was entrapped from October 1937 to January

1940. The wind-class ice-breakers (Fahey, 1945) commissioned during and after World War II are the best available to us. These displace about 5,300 tons, are 269 feet long, 63.5 feet beam, draw about 29 feet, and have 10,000 h.p. diesel electric machinery. They can successfully navigate fringe ice areas the year around, but are unable to move freely far within the Arctic pack at any time of the year. Considerable penetration can be made locally in summer, and perhaps greatly more on some years and in some localities than on other years and in different localities. Larger and more powerful icebreakers are invariably proposed. These presumably would give greater freedom of movement in the fringe areas and, given time and taking advantage of the summer conditions, might be able to cover most of the Arctic Basin. Regardless of the size and power of a surface vessel, however, it will not have complete maneuverability in ice areas at all times, and progress with respect to the ice will always be made at great expenditure of energy compared to operations in the open sea. On the other hand, submarines operating under ice and aircraft flying across ice areas do not make premium power demands.

The use of modern icebreakers has increased the knowledge of ice conditions both around the Arctic periphery and in the Antarctic. Within the ice, these vessels provide a stable working platform, living space for scientists, and a limited amount of laboratory space. Excellent electronic equipment and even helicopters for ice scouting can be carried aboard.

Some of the drawbacks of these vessels as oceanographic platforms are:

(a) Requirements for personnel and power are high.
(b) Complete maneuverability in ice is lacking.
(c) The five-fathom draft of the heavy icebreakers requires that the vessels keep well off shore in much of the Arctic, which is characterized by the world's broadest continental shelf.
(d) Their heavy roll prevents full efficiency in stormy weather outside ice areas. Any bilge keels or other external hull devices to damp the motion would need be retractable or they would be torn off by the ice.
(e) In heavy ice areas conventional oceanographic gear, such as dredges, plankton nets and the geomagnetic electrokinetograph (GEK), cannot be towed nor can bathythermographs be lowered under-way. A means for handling these under-way devices in ice areas is needed. No simple solution is apparent.
(f) Under the influence of the wind, the icebreaker drifts with respect to ice when on-station, resulting in drifting ice fouling the hydrographic line. Advantage can be taken of open areas when these are available. The ship is oriented with the sampling platform upwind and the lee side can be berthed on the windward side of a large ice floe to cut down relative drift. Devices for keeping ice cakes out of the line are needed. Prod poles, grapnels on a line, fire hoses, fenders and even frogmen have been tried as circumstances indicated but no simple solution has yet been found. A very sturdy retractable protective frame that could be lowered into the water at the beginning of a station might aid considerably in the more open ice. This device probably could not be used where lateral pressure is great or during winter when the broken ice occasionally has the consistency of gravel, resisting or even preventing the lowering of gear. Large wire angles experienced during strong winds also complicate protecting the wire. A pressure compartment in the bottom of the ship that could be opened to the sea for sampling purposes is worth considering. This might be somewhat similar to the diving compartment of the submarine NAUTILUS used by Wilkins and Sverdrup (Sverdrup

and Soule, 1933). Ready access would be provided through the ice under most conditions. The observers and equipment would be protected from wind and weather and the temperature could be controlled. With suitable modifications some gear might at times be streamed underway. Depressors might be used to keep the line clear of the propellors.

(g) The observers and equipment on deck are normally on the weather side and are exposed to the extremes of wind and temperature. Protection in the form of windbreaks, hot air ducts, and other devices have only been partly satisfactory. At low temperatures ice forms on the wire and prevents proper functioning of the messengers and meter wheel. Ice coats on the outside of the reversing bottles and interferes with their handling. Ice may also form in the bottles increasing the salinity of the residual water. The messengers freeze. Many of these difficulties can be alleviated by protecting the equipment from the extremes of conditions as much as possible, as for example, by making all preparations for sampling in protected spaces and promptly returning the instruments to protection as soon as they are removed from water. Equipment for cold weather operations should be simple, rugged, reliable and designed to operate under extreme temperature ranges. Manipulations should be possible with mittens. Plastic bottles are now used for impounding water samples and the thermal characteristics of plastics should make these materials desirable for other oceanographic equipment and gear.

(h) A difficulty arising from the ice rather than the vessel is that noncaptive gear, for example salt ballasted underwater cameras, will likely surface under ice and not be recovered.

(i) Present ice breakers cannot efficiently disembark personnel and "on ice" vehicles that might be used for observations from the larger floes. Suitable provisions for such disembarkation could easily be made and would materially increase the scope of investigations possible.

Heavy icebreakers have been used to only a small fraction of their potential capabilities in sea ice investigations. Much new data and knowledge can be gained using but slight modifications in present techniques and equipment.

Submarines - The use of submarines for oceanographic work in ice dates to the NAUTILUS expedition conducted by Wilkins and Sverdrup in 1931 (Sverdrup and Soule, 1933). Their original plans had been to cross the Arctic Ocean from Spitzbergen to Bering Strait or, failing this, to reach the North Pole. The loss of a diving rudder made travel under the ice impossible. Their goals were not acheived but they did carry out significant oceanographic investigations within the ice limits. Since that time submarines have operated in periphery areas of both the Arctic and Antarctic packs. The use of the submarine in oceanographic investigations is still restricted by the mechanical limitations and operational capabilities of the vessel itself and not by deficiencies of oceanographic instruments and methods. When the true submarine becomes available, it should be able to do almost any oceanographic work that can be carried out by surface vessels and do much of it easier. A "Jules Verne" class submarine offers the following advantages:

(a) Relatively free maneuverability is afforded in ice areas outside the continental shelf, although not in shallow water between the ice canopy and bottom.

(b) The platform is stable. It has been extensively used for gravity determinations at sea.

(c) Effects of weather are reduced to a minimum. The roll of an ice breaker in the open sea and its drift before the wind often limits sampling operations to a maximum wind velocity of 20 to 35 knots.

(d) A submarine can be designed to permit extensive observations while submerged.

(e) Much equipment can be hull mounted permitting measurements underway and at changing depth. Long electrical leads or sampling lines, and streaming gear can be kept to a minimum.

A big disadvantage of the submarine is its limited space for personnel and equipment. Instrumentation will need be pointed towards compact automatic or semi-automatic gear, requiring a minimum of space and operating personnel. Full advantage should be taken of direct recording, hull mounted instruments. Sampling methods may need to be extended to permit investigating the water above the submarine to the ice or surface by using floats. Ample precedent in the atmosphere has been set by the meteorologist. Conventional gear that is to be lowered on hydrographic lines should be as small as practicable. Chances of contamination within a pressure chamber should be less than on an exposed weather deck, thus favoring the use of micro-techniques. Microanalytical methods should be used for chemical determinations wherever possible. Present day trends in oceanographic instrumentation are towards micro and automactic methods and the environment of the submarine should be especially favorable to their development.

From an operational standpoint the submarine would presumably need detecting devices to locate targets on all bearings and vertical angles. These could be used to survey the lower surface of the ice as well as the bottom. Means of fixing position under water will be necessary, the degree of accuracy attainable limiting the oceanographic problems to be investigated. The microstructure of the submerged ice surface and sublying water can be determined almost irrespective of position in the ice area. Positions obtained by occasional contact with the surface, combined with DR when submerged, or from bottom topography, are accurate enough to give the "climatic" picture. Good fixes would be required for accurately charting the sea floor under the ice. Although a simple device capable of precisely fixing positions while submerged would greatly increase the scope of oceanographic work that could be performed, much useful work can be done by conventional methods and using available equipment.

Aircraft - Andree of Sweden was making preparations to reach the north pole by balloon in 1896 while Nansen and Sverdrup were still unreported from the FRAM expedition. With two companions he survived the crash of the balloon on the pack ice in 1897 but perished in camp after reaching land. Subsequent attempts made to reach the pole by both lighter-than-air and heavier-than-air aircraft first succeeded in 1926. More recently over-the-pole flights and ice landings have become commonplace. The use of aircraft has added greatly to the knowledge of the character and extent of the Arctic and Antarctic packs, and the water mass and depths of the Arctic Basin. Aerial scouting of polar and of fringe areas critical for commercial shipping is now a routine operation. Today planes supplement Coast Guard ships on the International Ice Patrol operating in the Grand Banks area.

Landings on pack ice have been made using both light and medium weight planes and various types of landing gear. The two-motor DC-3 (C-47 or R4D), grossing approximately 15 tons, appears quite satisfactory. Heavier planes would have a smaller choice of landing places. Lighter planes are deficient in range and load capacity. Wheels and skis both are used for snow landings. Small planes with floats can use ice puddles in summer. Recently frozen leads or leads of the winter that have not been broken and rafted since the original freezing make suitable landing strips. These can be found over most of the

Arctic throughout late winter and spring. Quick, reliable methods are needed for determining from the air the thickness of the snow cover, the smoothness of the ice and its thickness or load bearing strength. Methods should preferably be instrumental as visual observations are not trustworthy in snow areas. The upturned edges of local pressure ice, freeboard at edges of broken ice, and color are useful indications of thickness, but the "personal" factor is great. Seismic methods for determining ice thickness and other mechanical properties have been tried on various types of ice by Ewing, Crary, Press (Press and others, 1951) and others. The inhomogeneities and irregular thickness of sea ice can be expected to complicate any physical measurements, and averaging methods may not indicate the critical extremes. The large size, and apparently uniform character of freshly frozen, unbroken ice of the leads favor satisfactory measments of this ice, however. Preference for gear is completely plane enclosed, trailed, or non-captive in this order.

Conventional oceanographic equipment can be used from landed planes, but should be light in weight, compact, simple to operate, and positive in action at extremely low temperatures. Power, or its equivalent in gear and fuel, must be evaluated in terms of weight. Aside from normal oceanographic procedures, provision must be made for penetrating the ice to the water below. Ice spuds or chisels, augers and chain saws have been used. The newer hand power augers cut quite rapidly and give a core 2 to 4 inches in diameter, suitable for studying the internal structure and composition of the ice. Larger holes are required for lowering oceanographic gear. On Project Skijump (Holmes and Worthing, 1951) these were quickly made using a power chain saw and breaking the last several inches with an ice chisel. The winch was kept in the plane and the hydrographic wire was rigged out the parachute door over a boom to permit lowering the gear vertically. Cabin heaters kept the compartment warm enough to insure proper functioning of the reversing bottles and thermometers.

As in the case of the ice breaker and the submarine, the present oceanographic work is largely limited by the vehicle and is not due to lack of specific oceanographic instrumentation. The plane landing on ice can supplement the ship by occupying widely spaced stations well inside the pack perimeter, taking advantage of late winter and spring conditions. This combined geographic and seasonal gap cannot easily be filled by surface vessels.

Helicopters can be used from ship or beach for on-ice landings. They are excellent for short range reconnaissance and shuttle service from icebreakers. Their light load capacity, cramped space, short range, and inability to take off and land in strong winds limits the oceanographic tasks that they can perform. Logistically they cannot operate as independent units.

Long range reconnaissance aircraft fill quite a different need in sea ice studies than those satisfied by planes for making on-ice landings. These larger aircraft can describe the distribution of the ice; defining its limits, the seasonal and annual changes, the density and arrangement of the ice cover, and the character of the ice including form, size, surface characteristics and the like. Visual and electronic observations amplified by photography are commonly used.

Planes were used extensively during the war years to scout the ice of the North Atlantic from the Scotian Banks through the Greenland Sea to Bear Island. This dates the first approach to synoptic observations over that large area. The primary problems at that time were seeing the ice visually or by radar, determining the position of the plane and the relative position of the ice, and evaluating the character of the ice in terms of ships' operations.

Visual sightings were reliable in times of good visibility but ice could easily be missed in times of unreliable atmospheric conditions, a state more or less characteristic of sea ice boundary areas. Positions based on astronomical sights were frequently poor and loran coverage was incomplete. The evaluating of the character of the ice in terms of ships' operations required considerable experience and familiarity of the capabilities of the different class vessels. ·A ship skipper sighting ice for the first time from the air almost always overestimated what his vessel could do. After about three observation flights, alternated with ship attacks on the ice, estimates began to have meaning. Aerial observers not benefitting by shipboard experience learned more slowly. The real need is to keep the physical description of the ice, in numbers where possible, keyed to the ice itself and independent of the observation aspect, vessel capabilities and the like. Easily measured, easily understood and accurate physical descriptions are needed. The ice observers instructions and ice codes are a step in the right direction.

Radar viewing shows targets the strength of which are, in part, a function of the performance level of the instrument and the prevailing transmission characteristics of the atmosphere. Because of these and other variables, radar data is subject to serious misinterpretation. Successful scouting of sea ice limits and outlying icebergs has been made while blind using radar and loran but reliance is given here only to space and time extrapolation of visual sightings. Visual and electronic photography, with suitable interpretation keys, can be expected to increase the usefulness of aerial scouting.

Land and Ice Vehicles - The days of the individual assault on the sea ice frontiers by kayak and dog sled, the primitive amphibious-ice vehicle, are at end. A true ice-amphibian, however, light enough to travel over average ice but strong enough to pull itself out of leads and "break-throughs" would favorably extend the field of action of any vessel, shore or ice station. As an independent unit it would have limited range. For far afield operations it would need logistic support, presumably by air.

In winter, caterpillar tractors now operate on shorefast ice and the small amphibious "weasel" has been successfully used on pack ice. The wide treads of the latter permit rapid progress even across soft snow and comparatively light sea ice. Several "snowmobiles" have been developed for winter travel on land and some of these might be made amphibious. Presumably such a vehicle could be fitted out in the manner of a small oceanographic vessel. Oceanographraphic instruments would be similar to those used for on-ice plane landings. Here again the limitations are those of the vehicle.

It might be mentioned that for small ice parties the powering of the oceanographic winch presents difficulties. Hand power, foot power, wind power and various types of fuel powered, portable winches have been used. None have been satisfactory in all respects, notwithstanding recent attempts to improve them.

Arctic Stations - Arctic stations, such as the Arctic Research Laboratory of the Office of Naval Research at Point Barrow, the newer weather stations in the Canadian Arctic Archipelago, and the Air Force station on T-3 all provide for long continued observations of the "inshore" ice and weather peculiar to their locations. Problems such as times of freeze-up and break-up, growth rate of ice, ice-beach processes, and the effect of ice on tides can be investigated. The more readily accessible stations are convenient for testing certain sea ice equipment and making ice engineering tests. Although the stations are on the edge of sea ice, the moving pack is by no means easily accessible. Effectively, it may be as remote from the station as it would be from the interior of the continent.

The floating stations are comparable in many respects to the more isolated shore stations. They are subject, however, to transportation over considerable distances in the Arctic, uncontrolled and more or less unpredictable, and in this respect are comparable to a ship frozen in the ice. The problems to be undertaken would be of similar nature and much of the instrumentation would be the same. Consider Nansen's FRAM expedition (Nansen, 1897) and Papanin's drift on the ice floe (Papanin, 1939) allowing for the advances in science over the intervening years. The ice floe may provide more freedom in the geographic position of initiating investigations in the pack but this can hardly offset the advantages of comfortable living quarters and well equipped scientific laboratory of the ship. The floating station must be established and supplied by plane and later removed, barring natural catastrophe, by plane or, if late in the life of the ice floe, by ship. Considerable permanency may be expected, although not positively assured, on the so-called ice islands (Fletcher, 1951) (Koenig and others, 1952) as T-3 (Fletcher Island). The numbers of these are limited. Of themselves they afford many unique problems.

Supporting Electronic Gear Used in Navigation and Ice Detection - The electronic gear useful for detecting the presence of ice at sea are radar and sonar (underwater sound ranging). These devices were greatly improved during the war years for target location without, however, any alterations for the explicit purposes of studying the ice. The detection of ice by radar is essentially the same problem as that of any other floating target. Although the echo from an iceberg is weaker than that from a steel ship of comparable above water size. In cases of unusual channeling near the sea surface, icebergs have been detected at distances approaching 100 miles but the normal range is more frequently 10 to 50 per cent of this distance. Sea ice is detected at ranges up to ten or more miles. In rough seas, isolated cakes or small bergs may be obscurred by sea clutter on the radar scope and missed entirely. Within the ice limits seas are normally smooth and radar shows the open leads. Beyond a few miles reliability decreases rapidly with distance. It is anticipated that devices used to minimize sea clutter will be as effective on ice as they will be on other types of targets.

The problem of target identification by radar, distinguishing ice from other targets, is still with us. Indirect methods using relative motion are useful, but there is little difference in quality of echo from a drifting dory or an ice cake.

Sonar perhaps suffers more in picking up ice than other targets. This is in part due to the irregular water structure with marked gradients in temperature and salinity that frequently occur near pack ice peripheries. Ice targets may be missed entirely by this device. Mechanical improvements in sonar, enabling it to better detect submerged or floating targets, will be effective on ice where the water conditions favor suitable transmission.

Next to detecting the ice itself, the defining of its geographic position is perhaps most important. Ice areas are notoriously bad for determining position by astronomical navigation. In high latitudes, when weather is not overcast or stormy or foggy, refraction may be quite serious. In the Grand Bank area, it is possible to cruise days on end without suitable astronomical fixes.

The installing of loran stations during the war years greatly assisted the navigator in determining his position. Using loran and radar, it was possible to scout the boundaries of ice fields and off-lying bergs from ship or plane. Improvements in the accuracy in loran for ship and plane navigation will to the same extent increase the accuracy of defining the position of ice encountered.

Shoran is another device used for precise positioning over line-of-sight distances. Because of its limited range, it is of little value in the defining of pack ice limits.

The electronic-position-indicator, recently developed by the Coast Survey for offshore survey at distances of 12 to 500 miles, is useful in surveying sea ice areas. Its great accuracy (average error 0.2 microseconds for a series of tests at ranges of 45 to 90 miles) permits the drift of a vessel on station to be determined in a relatively short period. By measuring the movement of ice relative to the water mass, it offers a means of obtaining ice drift and the vertical current structure by direct observation. It is especially valuable for bad visibility areas in which the conventional methods of navigating fail or are lacking. Using it, detailed offshore soundings can be expected to increase greatly in value.

## PHYSICAL AND CHEMICAL PROPERTIES OF SEA ICE

The study of the physical and chemical properties of sea ice is complicated by the fact that it is not a pure compound, but a non-homogeneous, ever-changing mixture of ice and the sea salts containing occluded brine. The relative amounts of brine, salt crystals and ice present is dependent upon the salt content of the original sea water, the rate of freezing, age, temperature and the thermal history of the ice since it was first formed. Freezing and thawing freshens sea ice as a whole and causes a change in the distribution of brine and salt within the ice. Ice fields move under wind and current. Pressure built up by the relative movement within the field or at the edges results in large scale rearrangements of the ice from cakes turning over, over-riding one another and interleafing, and ice cakes originating hundreds of miles apart occasionally intermingling with each other. Snow cover and new-formed ice contribute to the physical discontinuity of the new configurations. The structure of newly formed winter ice of simple thermal history from a given locality that has not been subject to breaking and rearrangement, is less complex. Furthermore, ices differing in origin and history, when sufficiently aged, may be freshened to the extent that a close similarity of properties exists, determined largely by the existing thermal structure within the ice. Dichtel and Lundquist's (1950, 1951) investigation of the physical and electrical characteristics of comparatively simple sea ice are among many which show even its great variablity. In making and interpreting physical and chemical measurements, allowance must be made for the more or less confused arrangement of the ice, its variable composition and continuously changing properties. It is necessary to measure many of the physical and chemical properties of the ice in situ to avoid changes that would accompany removing and storing the samples.

Physical properties of ice now being studied or contemplated, include the mechanical, thermal, acoustic, optical and electrical. Chemical investigations include those of salt and gas content, ion ratios, freezing, thawing and related processes, as they affect the salt-water-ice system; foreign substances in ice, ice aging processes, history and dating of ice. The necessary measurements can largely be made by existing instruments or simple modifications thereof. Progress made in solving many of the problems recognized as early as the FRAM expedition has not been in keeping with the instruments directly available or adaptable. A continuing and intimate contact with ice problems of an adequate number of well trained scientists has been lacking. Not more than one or two full time oceanographers in the United States have devoted their efforts primarily to the study of sea ice, and no schools give specific training and instruction in the field. The present deficiency in knowledge of sea ice stems primarily from shortage of scientific personnel and inadequate facilities and not as yet any fundamental deficiency in instrumentation.

## INTERACTIONS OF ICE AND BOUNDING MEDIA

Ice reacts in various ways across its interfaces with sea, air and land. The sea and air in particular affect the formation, movement and disintegration of ice. Ice affects the temperature and salinity of the water, the temperature of the air and the transport of energy and mass from sea to air. It gives an effective wintertime extension of continental limits with attendant effects on local marine weather. It reduces wave motion in the sea on the one hand and, as it retains fresh water in freezing, sets up convective currents within the sea, on the other. Ice erodes beaches and shallow bottom areas and transports terrigenous materials far seaward. Characteristic fauna and flora are associated with sea ice areas.

Numerous studies are being made of the interrelationships between ice and its environment. Our knowledge, however, of properties and processes is still too meager to make valid, long range predictions of ice conditions. These have been tried for both icebergs and pack ice. Even short range predictions must be, in general, qualified. Existing gaps can be narrowed by reconnaissance and climatic type studies, investigations in situ of the intimate properties and processes of ice itself, and laboratory experiments under controlled conditions. With increased intensity of effort, the instrument ceiling may be reached sooner than anticipated. Efforts should be made first to adapt the best of appropriate present day instrumentation to sea ice studies, and next to develop new instrumentation as needs are indicated. It is suggested that this be done by increasing the over-all effort devoted to sea ice studies and not by shift of emphasis within the present group of investigators.

## CONCLUSIONS

1. Conventional oceanographic and related instruments can, in general, be used for sea ice studies with but little modification. Much new information can be gained from their use.
2. Instrument design should be keyed to the facility, ship, plane or submarine affording contact with the ice, as well as to the problem being studied.
3. Studies of sea ice are not progressing at an optimum rate. Inadequate facilities for contact with ice, failure to use present facilities to their fullest extent, an insufficient number of participating scientific personnel, and lack of formal instruction and training in the field are factors to be considered.

## DISCUSSION: Waldo K. Lyon

My remarks are only an echo to those of Clifford Barnes. Sea ice is a transient boundary state of the sea; a complex of discontinuities much in contrast to the normal continuum of the oceans. The meagerness of our knowledge makes discussion difficult. We cannot write down an expression which will describe the chemical or physical structure of sea ice, though such structural complexes as glasses, ceramics, rubbers, etc. can be described.

Inspection Phase - As with every problem, the first approach is the descriptive exploration stage -- the inspection phase. Historically, the seas having perpetual sea ice were the last to be explored, and consumed the major exploration effort done during the last century. The exploration phase has carried well over into the first part of this century, but during the past thirty years we have seen the transition to the second phase, that of quantitative measurement. If a starting point be named, it is likely H.U. Sverdrup and the Maud

Expedition in 1920. In contrast, exploration has continued principally by air as witness Byrd, Wilkins and others.

These remarks are the preface to emphasize that the designed measurements -- quantitative phase is all important; yet, I assure you, in the planning of expeditions even now, the exploration -- inspection--qualitative point of view often rises to threaten the real objectives of an expedition. Quantitative measurements necessarily mean a correctly engineered vehicle, instruments and techniques and qualified investigators.

Sea Ice - Water System to System Interchange - A very considerable amount of data has been gathered on the sea water phase beneath the ice. Obviously, the sea water phase is influenced by the heat and salt exchange features of the ice system. The observation techniques and sampling instruments are the same as those for the conventional non-ice sea, except for the changes in actual handling which result from cold weather and loss of mobility, and have been discussed in the paper. The cost per datum is much higher for the ice covered than for the non-ice sea in manpower, horsepower and dollars because of the vehicle -- icebreaker, submarine or aircraft -- that must be used; and because of the plain hardship of the work. The loss of surface ship maneuverability, of course, negates the customary procedures for underway devices, e.g. the GEK, or sound propagation measurements.

Sea Ice Equation of State - Methodology for study of the sea - ice phase, the boundary layer itself, cannot be dismissed by borrowing from the oceanography of non-ice seas. The physics of sea ice has no apparent direct parallel in other geophysical problems to which we can turn, except for the observation techniques of glaciology.

Sea ice confounds description in that it is a mixture of many phases, principally water crystals, sodium sulfate and sodium chloride crystals, brine and air bubbles. The phases are always under action of heat flow from the sea beneath to the atmosphere with resulting variable temperature gradient and are also effectively influenced by the gravitational force field. It is a transient phenomenon of irreversible processes, the true equilibrium states being the end points of no ice before and after the freezing-melting process.

Laboratory studies beginning with Ringer in 1907, and others since, are studies in closed systems at one temperature giving equilibrium states of sea ice. These plus the field measurements of Malmgren during the Maud Expedition provide the bulk parameters, heat conductivity, density, salt content, etc. which permit calculation of interchange between the sea and the sea ice taken as a system.

Measurements have not been made of the structure within the sea ice system. We cannot write down functions describing spatial distributions of the phases within this mixture, nor the migration constants for any phase; for example, brine cells or air bubbles. Cross-sections and corings have been taken in the field which give single distribution patterns, but of course these observations are singularities because the functions describing the controlling parameters from initial freezing to time of coring are unknown. Moreover, the observations procedure so disturbs the sample that subsequent study of the sample will not give the in situ conditions.

It is likely only lack of imagination, but further field observations of system properties as density, heat conductivity, temperature gradient, etc., seem unwarranted until laboratory studies begin to give models of the internal mechanics and thermodynamics of sea ice. The work must be done in the laboratory where the time, pressure and temperature functions are under control and known. The studies should be on sufficient scale to work with the transient phenomenon, as well as continuation of work with equilibrium states in calorimeters. For example, perhaps dye tracers can show brine cell migration.

From the laboratory, perhaps, will come a quantitative type description of sea ice in terms of a set of equilibrium states and changes therefrom, with variations of the intrinsic parameters, the temperature, the pressure, molal ratios, etc. Without this, what further can be done in the field with the electrical conductivity studies of Dichtel and Lundquist, except to just repeat their measurements? You find they did their work very neatly and well.

Sea Ice Dynamics and Acoustics - In contrast, however, certain field studies are needed; some because they will be the first measurements, others because they will give extensive properties of the sea ice system. Considerable work and techniques are being mastered by A. P. Crary and associates for the study of propagation of flexural waves by the ice sheet and sound propagation in the air above it. However, sound propagation in the sea beneath the ice has not been studied; reflection and scattering coefficients are unknown even as to order of magnitude. The instrumentation, but not the ships, can be borrowed from propagation work in non-ice oceans. The need that the sending and receiving ships separate from each other over known and controlled distances, points to the use of a submarine which can move under the sea ice. In addition, the submarine is needed to measure the underside profile of the sea ice along the transmission path. At low sound frequencies, the underside roughness parameter of the sea ice should considerably influence reverberation and reflections along the transmission path. At high frequencies, the bubble distribution and size within the sea ice are likely governing parameters. Whether a submarine can carry out this task is a mute question. The Nautilus in 1933 penetrated under the ice one boat length, which hardly answers any questions.

Though the instrumentation for sound transmission studies is available, the vehicles, icebreaker and submarine, are strictly a naval problem both as to availability and operating cost. Even one transmission run would tell a great deal; however, a long, extended, set of measurements might add little more unless taken in step with equations needed to describe the internal mechanics of sea ice.

Other field problems that can profitably be done now, concern sea ice dynamics. During the recent winter expedition of the icebreaker, USS BURTON ISLAND, we attempted to measure the force fields that must be present in sea ice sheets when differential motions are taking place between parts of the ice field. These are manifest by shearing of the ice sheet and the resulting rafting or tenting. We had simple crusher gages in the form of various sized tin cans which we buried. In addition, a heavy ribbed box was built with diaphragms for walls. The diaphragm deformations were measured by strain gages in order to record magnitude and time characteristics of pressure pulses that likely pass through the ice sheet. However, I am sorry to report that during the entire expedition, no rafting occurred in areas we could reach. The wind prevailed from one direction; differential motions were not generated. This type of ice dynamic study has yet to be done, and places the rather rugged requirements on the vehicle that it be capable of living in the winter ice or that it must get the men and equipment to the ice and maintain a camp thereon.

Work has not been done on the shear strength or mechanics of shear and crystalline fracture, though such studies are of high import to ship design. For an icebreaker, should the design of the prow be an art based on trial and error? Or, what in icebreaking ability is bought if the power of the breaker is raised from the present 12,000 to 20,000 h.p.? The question of measuring shear has not been considered, yet alone instrumentation developed.

Of course, synoptic studies of sea ice coverage and movement can continue for a long time in the field and the success, as has been mentioned, depends on improvement in extending observation stations and methods, and on improved reporting and classification. Long term field work appears warranted.

In view of these remarks, it would appear we should expend the effort to build or find facilities that can handle sea ice studies. To further glaciology, laboratories have been built in close proximity or even within glaciers. However, living like a mole inside a chunk of sea ice is not particularly appealing. Any laboratory facility for the study of sea ice should be of sufficient size to handle realistically the transient phenomena and to permit, for example, acoustic measurements and mechanical properties tests.

The laboratory facility for ice study should be designed to permit measurements within the ice sheet and in the water phase below the ice. The time-pressure-temperature functions of this sea ice should be known and under control. There are many facilities for study of problems of the snow-ice and air phase above, but no facilities for study in the water beneath. The correction of this deficiency seems a principal first task in instrumentation for study of the internal mechanics of sea ice. Its cost is comparable to that of one field expedition.

The U.S. Navy Electronics Laboratory maintains a small observation station at Cape Prince of Wales overlooking the Bering Strait for the purpose of studying relationships between the sea ice system and the particular oceanic system of the Chukchi-Bering Seas. Water, ice and heat transport through the Strait is monitored at the station throughout the year. Much effort at the station has and continues to concern field instrumentation and procedure, ranging from schemes for laying cables across beaches bull-dozed by ice to photographic methods of recording sea ice movement -- a whole discussion in itself. The Cape Prince of Wales location has seemed more pertinent to our work than the Arctic Research Laboratory at Pt. Barrow because the sea ice flux is within immediate reach from the beach. Moreover, the Bering Strait is a singular location connecting two oceanic systems.

In quick summary, the five essential needs are:

(a) Costly, specialized vehicles, submarine and icebreaker; the cost per field datum is very high necessitating excellent planning.
(b) Laboratory facilities and studies.
(c) First field studies in sea ice dynamics.
(d) A set of equations of state for the phase mixture, sea ice.
(e) Investigators.

To reemphasize the point made by Dr. Barnes, the needed investigators are not to be obtained by shifting present workers in the many oceanographic fields, but by growth of interest from outside, i.e., by new blood coming up. Yet how is this to be done except through the schools represented here today? Are you, or can you include the physics of sea ice in your curricula; can you find an instructor? Sea ice is just as surely a regime of the sea as the marine organisms, the circulation system or the chemistry.

## DISCUSSION: John F. Holmes

I believe Dr. Barnes and Dr. Lyons have covered the subject of the Arctic very completely. There is only one point I wish to add and assign my own set of values to, and that is: The major difficulty in making any scientific observation is transportation of men and equipment across the Arctic ocean. I believe suitable transportation amounts to 90% of the problem of oceanography in the Arctic.

My experience has indicated that the present oceanographic instruments will be as useful in the Arctic Ocean as in any other ocean. The ice cover may be more of an assest than a barrier. We found that we could make a station in almost the same elapsed time on the ice field as could be made on rough ocean.

## DISCUSSION: William G. Metcalf

I believe that the combination of Dr. Barnes' paper and Lyon's remarks concerning it are extraordinarily complete. There is only one thing which I should like to add -- something which we did not suspect at the time of the symposium.

The use of plastic bottles for impounding water samples in the Arctic is mentioned. Both on recent aircraft operations and on the ice island, T-3, we have had very discouraging experience with plastic bottles. It seems that their high rate of shrinkage in low temperatures frequently forces brine out of the bottles no matter how tightly the cap is put on. In an extreme case on T-3, a sample was reduced in salinity by more than 15 parts per mille. Many cases of losses of from $\frac{1}{2}$ to 2 or 3 parts per mille have been observed.

As a result of this, we have lost a very fair share of the salinity data which was gathered at great trouble and expense. If we can prevent others from making the same mistake, then at least the difficulties we had will result in some good being done.

## REFERENCES: Barnes

DICHTEL, William J., and LUNDQUIST, G.A. 1951. "An Investigation into the Physical and Electrical Characteristics of Sea Ice". *Proc. of Alaskan Science Conference, 1950. Bull. of Nat. Res. Counc. No. 122. pp. 122.*

FAHEY, J.C. 1945. "The Ships and Aircraft of the United States Fleet". *Victory Edition. Ships and Aircraft, New York. p. 82.*

FLETCHER, J.O. 1951. "Floating Islands in the Arctic Ocean". *Proc. of Alaskan Science Conference, 1950. Bull. Nat. Res. Counc., No. 122. p. 122.*

HOLMES, J.F., and WORTHINGTON, L.V. 1951. "Project Skijump". *Woods Hole Oceanographic Institution. Tech. Rept. Ref. No. 51-67. pp. 1-66.*

KOENIG, L.S., GREENAWAY, K.R., DUNBAR, M. and HATTERSLEY-SMITH, G. 1952. "Arctic Ice Islands", (Parts 1-4). *Arctic. Vol. 5, no. 2, pp. 67-103.*

NANSEN, FRIDTJOF. 1897. "Farthest North". *Archibald Constable and Company, London. Vol. 1, pp. 1-510, Vol. 2, pp. 1-671.*

PAPANIN, IVAN. 1939. "Life on an Ice Floe". *Julian Messner, New York. 1939. pp. 1-300.*

PRESS, FRANK, CRARY, A.P., OLIVER, J. and KATZ, S. 1951. "Air-Coupled Flexural Waves in Floating Ice". *Trans. Am. Geophys. Un. Vol. 32, no. 2, pp. 166-172.*

PRESS, FRANK, and EWING, M. 1951. "Propagation of Elastic Waves in a Floating Ice Sheet". *Trans. Am. Geophys. Un. Vol. 32, no. 5, pp. 673-678.*

SVERDRUP, H.U., and SOKLE, F.M. 1933. "Scientific Results of the Nautilus Expedition, 1931". *Papers in Physical Oceanography and Meterology. Vol. 2, no. 1, parts 1-3, pp. 1-76.*

U.S. NAVY HYDROGRAPHIC OFFICE. 1946. "Ice Atlas of the Northern Hemisphere". *pub. No. 550. pp. 1-106,* 1952. "A Functional Glossary of Ice Terminology". *Pub. No. 609. pp. 1-88.*

## REFERENCES: Lyons

U.S.NAVY HYDROGRAPHIC OFFICE. "A Functional Glossary of Ice Terminology". *Pub. No. 609, Washington, D.C., p. 88,* 1952.

DICHTEL, WILLIAM J. and LUNDQUIST, G.A. "An Investigation into the Physical and Electrical Characteristics of Sea Ice". *Proc. of Alaskan Science Conference, 1950. Bull. of National Research Council No. 122, 1951, p. 122.*

FAHEY, J.C. "The Ships and Aircraft of the United States Fleet, Victory Edition". *New York, N.Y. 1945. p. 82.*

FLETCHER, J.O. "Floating Islands in the Arctic Ocean". *Proc. of Alaskan Science Conference, 1950. Bull of National Research Council, No. 122, 1951. p. 122.*

HOLMES, J.F. and WORTHINGTON, L.V. "Project Skijump". *Technical Report No. 51-67. Woods Hole Oceanographic Institution, 1951. pp. 1-66.*

U.S.NAVY HYDROGRAPHIC OFFICE. "Ice Atlas of the Northern Hemisphere". *Pub. No. 550, Washington, D.C., 1946. pp. 1-106.*

KOENIG, L.S., GREENAWAY, K.R., DUNBAR, M. and HATTERSLEY SMITH, C. "Artic Ice Islands". *(Parts 1-4), Arctic, Vol. 5, No. 3, 1952. pp. 67-103.*

NANSEN, FRIDTJOF. "Farthest North". *Archibald Constable and Company, Westminister, England, 1897. Vol. 1, pp. 1-510, Vol. 2, pp. 1-671.*

PAPANIN, IVAN. "Life on an Ice Floe". *Julian Messner, New York, 1939. pp. 1-300.*

PRESS, FRANK, and EWING, M. "Propagation of Elastic Waves in a Floating Ice Sheet". *Trans. Amer. Geophys. Union, 1951. Vol. 32, No. 5, p. 673-678.*

PRESS, FRANK, CRARY, A.P., OLIVER, J., and KATZ, S. "Air Coupled Flexural Waves in Floating Ice". *Trans. Amer. Geophys. Union, 1951. Vol. 32, No. 2, pp. 166-172.*

SVERDRUP, H.U. and SOULE, F.M. "Scientific Results of the Nautilus Expedition, 1931". Under the Command of Capt. Sir Hubert Wilkins. Papers in *Physical Oceanography and Meteorology, Cambridge, Mass. 1933. Vol. 2, No. 1, pp. 1-76.*

ZUBOV, N.N. "The Drift of the Ice-Breaker SEDOV". *Nature, 1940. Vol. 145, pp. 533-539.*

# ACOUSTIC INSTRUMENTATION AS A TOOL IN OCEANOGRAPHY

J. B. Hersey

## INTRODUCTION

Acoustic waves travel readily in sea water whereas all electromagnetic waves are rapidly attenuated. Consequently, except for rather short range examination, as is now achieved in underwater photography and television the only means presently developed, or likely to be available, for perceiving objects or events at considerable distances underwater is by sound. The sound perceived may be the natural sound generated by the object or event, as a sound-making fish or a submarine landslide, or it may be an echo from the object under study. The techniques described above have to do with sensing the presence of objects in the water or with analyzing the characteristics of things or events by the sound generated or re-radiated by them. The physical properties and structure of the water itself can be studied by analyzing the alteration of the intensity and character of the sound received from a known source as the relative position between source and receiver is varied. In addition there are various laboratory techniques for studying the physical properties of sea water. In some instances these are capable of working at sea, thus providing the oceanographer with a potentially valuable tool. This area of the art of underwater sound is the least developed outside of the laboratory.

The Nature of Acoustic Data - Virtually all acoustic observations underwater are made with the aid of a transducer which transforms a part of the energy from the acoustic wave to electrical energy in a circuit which, in turn, feeds some sort of electronic device. This drives some sort of presentation device which may be any of several types of recorder, a momentary visual display on an oscilloscope, or earphones or loud speaker. In common with most problems of instrumentation, systems for recording or analyzing acoustical data have a more or less vaguely limited range of usefulness for various problems. For example, the directional discrimination of a hydrophone varies with the frequency to such a degree that it is totally satisfactory for a given prescribed job only over a rather limited part of the spectrum. On the other hand, the same hydrophone is appreciably directional over a much broader spectral range and may well be usable for certain other problems so long as this variation is tolerable. Again, it is usually not practical to build an amplifier that has a constant gain over the whole range of frequencies of interest. Certain departures from such a "flat" response may be acceptable and often are desirable for some problems but not for others. All types of recorders distort the electrical signal fed to them by the amplifier. The nature and degree of the distortion must be known in greater or less detail for proper interpretation of the results. The list of these properties of acoustical instruments could be extended considerably. However, it is reasonable to expect that for a given problem instruments can be designed to serve the needs of the problem within limits that can be known. In any event acoustical instruments in general have rather complicated performance characteristics, and must be understood to a considerable degree by anyone who assays to interpret results from them.

Even where the design of an electronic system is adequate a continuing and vexing problem is assuring stable, reliable performance. This is well known to many more people than have any real understanding of electronics. As a result we are all properly suspicious of any information that has passed through a vacuum tube circuit. This sort of suspicion runs riot on occasion, and can be quite dangerous scientifically, causing the investigator to ignore significant data on the plea that it was "some sort of electronic difficulty". This is an understandable attitude, but nevertheless, it is usually the result of not understanding one's tools. However, if an electronic system has been properly designed and tested for a specific job and is maintained as is required by the nature of it, it can be quite free of spirits and spooks. As a final note of suspicion, it is usually well to include circuits in the system that can test its reliability in the field.

In what follows acoustical instruments will be discussed in groupings according to the general type of problem in which they are commonly used. I shall try to describe in a general way the state of the art in each area, indicating the sort of instruments that are readily available to oceanographic research. These general groupings are: passive listening, acoustic ranging, sound transmission studies and echo-sounding and echo-ranging. I have had little acquaintance with acoustic laboratory techniques as opposed to broader scale field observations. Consequently, I hope this interesting field will be discussed by the other physicists later.

## PASSIVE LISTENING INSTRUMENTATION

This technique is employed whenever the primary object of study is either man-made or natural sound, rather than the transmission characteristics of the medium. Broadly speaking this is the study of ambient noise; that is to say, the sounds heard at any given location caused by human activity or other natural agents. It may be used to detect the presence of and even locate ships, noise-making animals, submarine landslides, distant storms, approaching rain squalls, and seismic activity within the Earth, thus providing a basic observational tool in these several parts of oceanographic science. The quantitative study of ambient noise intensities caused by breaking waves, rain on the water, and other sounds caused by meteorological effects provides data which may well contribute to the study of energy interchange between the atmosphere and the ocean.

Until now most of the effort in this technique has gone into naval problems such as the detection of enemy shipping. The ambient noise of the sea forms the noise background which limits naval detection just as the self noise limits an amplifier, and consequently some attention has been devoted to the spectrum of ambient noise in a variety of locations typical for naval operations. A by-product of this work during the last war was a study of the sound-making habits of a small number of noise-making fish, crustaceans and cetaceans in their natural habitat. These observations have provided a jumping off place for scientific work. We know the order of magnitude of noise caused by moderately high winds, and we have a good impression of how quiet the sea may be on a very calm day, but this knowledge is confined to the portion of the spectrum between 100 cps and 10 kc. We also know something about the characteristic sounds of some noise-making sea animals. Beyond this we know very little. This is the case largely because very few people are using this tool in oceanographic science. Passive listening gear is the simplest sort of acoustic system with which to observe. However, if it is to be used for any purpose save that of listening to and evaluating qualitatively the sounds of nature it may be demanding and complex. In the past ambient noise has been studied for the most part with non-directional hydrophones. This study has now reached the state where knowledge will be most readily advanced with directional systems. I shall discuss only the non-directional systems in the hope that the other acousticians will be prepared to describe the sort of directional properties that can be achieved and the complexity of instrumentation required for the various frequency ranges.

Observations are frequently taken from shore, but usually some sort of boat or ship is required to go where the problem is, or perhaps merely to get away from the excessive self noise of the shore. The first requirement on the boat or ship is that it be capable of sitting quietly in the water. No refrigerators, no galley range, no main generator can usually be tolerated in operation while observations are in progress. Electric power for the electronic gear is preferably obtained from storage batteries which power a small motor generator set which is very carefully shock mounted to isolate its vibrations from the ship. In short the ship is de-commissioned except for this single power system. When operating from small craft very light convertors or vibropack power supplies similar to those used for automobile radios have been used. A small rowboat has been used successfully to carry a complete amplifying and recording system powered by a 6 volt storage battery, B batteries and a vibropack.

For non-directional listening and also the simplest directional systems the principal instruments are the hydrophone, an amplifier, earphones and usually a recorder. There is available an array of essentially non-directional hydrophones sensitive to the audible range of humans. In this frequency range the workhorse of our group and many others is the Brush Development Company's AX58 series. A higher quality, but somewhat more fragile instrument is the Bell Telephone Laboratory's 5E. Both are World War II designs.* The AX58 types generate about one ten thousandth of a volt when in a plane sound wave whose pressure is 1 dyne/cm$^2$. The 5E has about one third this response. Their response to greater or lesser pressures is approximately linear over a considerable range. They are both usable with suitable modification of their pre-amplifiers from well below 10 cycles per second to about 10 kilocycles. Above this frequency their directional properties make them unsuitable for most quantitative work. At higher frequencies various hydrophones have been designed for non-directional reception. I am not thoroughly familiar with any of them, but understand that the Brush Development Company makes a useful instrument. One word of warning about high frequency hydrophones as a class is worth observing. Comparatively few of them are non-directional except in one plane, and the designer of the particular observation must bear this carefully in mind.

If adequately quite pre-amplifiers and amplifiers are used with either the AX 58 or the 5E the self noise of the listening system can be made somewhat quieter than the quietest ambient noise thus far observed at sea between 30 cps and 20 kc. So far as I am aware the same can be said for systems designed for use above 20 kc. However, the use of small assemblages of sensitive elements in the hydrophone to avoid directionality in this range makes for a less sensitive hydrophone, which, in turn, means a relatively higher self noise except where the impedance of the sensitive element can be kept low. High quality hydrophones operating at high frequencies with low self noise are normally designed to be resonant hydrophones operating in the neighborhood of resonance. At frequencies below 30 cps there is no considerable body of quantitative experience at sea. The principal problems in this region appear to be in the proper quiet handling of the hydrophone rather than electronic design.

---

* - Several hydrophones are being produced by various companies. These are just beginning to be used by The Woods Hole Oceanographic Institution but at this writing we can give no evaluation of them for underwater acoustics as applied to oceanographic research.

Whenever directionality is desirable in the hydrophone system, which is frequently the case, single hydrophones having large directivity indices are available only in the region above about 10 kc. Of this type a well known example is the early World War II QBE, a directional transducer designed for an echo ranging system operating at 24 kc. It has all the disadvantages of a tuned system, but is not so sharply peaked that it is completely useless at other frequencies. For the low frequencies the designer is on his own and may construct any of a wide variety of hydrophone arrays to suit his particular requirements from the simple "figure 8" pattern of a two element array to the sharply directional multi-element arrays. There is no circuitry generally available with any considerable body of experience behind it for the use of arrays in the low frequency field. This lack is becoming a serious shortcoming as field observations and understanding of this part of acoustical research progress.

The choice of amplifier and recorder used in taking field data is determined by a number of factors, some of which are not the least bit obvious at the outset except to experienced investigators who have suffered from past failures. For example, shall a high quality recording of the sound be attempted for relatively short periods, or will it be more advantageous to obtain a recording of lower quality which can, nevertheless, be made continuously over long periods of time? Is it wise to use some photographic process for recording that requires the records to be developed a considerable time after the tests? High quality records may result but you are assured that you won't know your data until it's too late to change a faulty procedure or try a new idea. Shall rather complete reliance be placed on the "quick and dirty" answer to be obtained from visual observations on a sound level meter or perhaps some such crude recorder as the type which records sound intensity as relative blackness on a chemical recording paper? The list could be continued. The state of understanding in the particular problem and the object of the particular observations are usually supposed to be the principal determining factors. Actually acoustical research groups as well as individuals seem to have developed rather arbitrary preferences in recording and subsequent analysis. For such standards as there are, underwater acoustics is wholly dependent on such related fields as air acoustics and seismology.

In passive listening one is usually interested in the quality as well as the intensity of the sound, and earphones or loudspeakers are apt to be used for observations somewhat more than an output meter. Except for the crudest sort of tests it is desirable to make some sort of recording that can be played back at a later time for analysis. The usual hydrophones, such as those mentioned above, have so low an output for sounds ordinarily to be heard that some sort of pre-amplifier is required between the hydrophone and any commercial recorder. While it appears on the surface that a stage or two of amplification with perhaps a third stage of cathode follower for matching is all that is required for the job, it has been our experience that a sufficiently versatile pre-amplifier for more than a very restricted use ends up as a rather high gain amplifier incorporating within itself provision for covering a very wide dynamic range and a wide choice of filtering, as well as built-in conveniences for electrical calibration. Such an amplifier is not required to take high quality observations, but it is a great time-saver in a continuing and somewhat varied acoustical research program. We started the development of such an amplifier in 1947 and called it, somewhat hopefully, the SUITCASE. I shall describe it briefly as an example of a rather versatile amplifier for passive listening.

In the beginning it was intended to be sufficiently portable that one man can carry it as hand baggage. For various reasons the SUITCASE has become an instrument which occupies a 12 x 17 inch rack mounted chassis and requires at the least a rather heavy alternating current power pack to operate it. The other alternative is a heavy duty 6 volt storage battery plus seven heavy duty B batteries. It is no longer regarded as one man's hand baggage. This amplifier contains two channels which may be connected separately to two hydrophones or in parallel to a single hydrophone. Both channels have a flat response with a minimum of phase distortion between 10 cps and 30 kc. They are designed to be fed by a low impedance line usually coming from a cathode follower contained in the hydrophone. No transformers are used in the basic amplifier, thus avoiding the distortion caused by them. The wide dynamic range is provided by designing the basic amplifier so that it will give an undistorted output of 1 volt across 500 ohms for an open circuit voltage input on the hydrophone crystal of about $0.5 \times 10^{-6}$ volts compared with an equivalent self noise of about $3.0 \times 10^{-6}$ volts in a frequency band 20 kilocycles wide when used with an AX 58 hydrophone. It further provides two step attenuators, allowing between them 120 db of attenuation in two db steps. That is, sounds whose pressure ranges over a factor of a million can be made to pass with small distortion through the amplifier. The maximum dynamic range of the suitcase at any given setting of the attenuators is about 50 db when properly adjusted. Obviously such a dynamic range cannot be realized for all settings and must be investigated for each use. The important point in the design of this instrument is the placement of the attenuators with reference to the stages of amplification. These attenuators are so placed that with proper manipulation the only vacuum tube preceding them is the cathode follower in the hydrophone, which will take about 10 volts on its grid without distortion. Two interstage filter positions are provided in each channel. A vacuum tube voltmeter is built in with selector connections to the output of either channel as well as to the input of a calibration circuit designed to introduce an electrical calibration signal in series with the crystal of either hydrophone.

The 1 volt output is adequate for feeding any of the common commercial recorders of the disc or magnetic wire or tape variety. It is not adequate for driving the pen of any of the common direct writing recorders. For this use separate drivers have been designed which will feed pen recorders full wave signals within their frequency response range, or rectified and averaged signals for higher frequencies.

For recording ambient noise, animal sounds and complex sounds in general the magnetic tape recorders have proven to be the most satisfactory sea going instruments having adequately broad frequency response. This does not mean that disc recorders, magnetic wire recorders or any of the photographic recorders may not be used, but they have severe limitations in one direction or another. Disc recorders require very close attention and do not operate too satisfactorily on a rolling ship. Wire recorders have a restricted frequency response, and the photographic recorders, while excellent for many purposes require considerably more technical skill and attention than the tape recorders, thus reserving their use for special problems. This general class of recorder stores the data so that it may readily be played back, providing a more or less accurate electrical copy of the original sound pressure fluctuations. We now feel that this sort of record should be made of most underwater sound observations. However, other presentations are required for various types of analysis.

The analysis of a passive listening observation may consist of determining the power spectrum, if the sound is approximately random noise or a steady state sound. This may readily be done with a series of band pass filters feeding one meter in turn or, for multichannel operation, several meters simultaneously. However, the usual technique now employed is to play back the previously recorded observation through the appropriate filters to a meter. The design of the meter is somewhat arbitrary, and there are engineering standards which it is frequently desirable to follow so that the results are readily to be compared with others. The nature of the sound will determine the design of the filters required for its analysis. For many ambient noise studies rather broad band pass filters suffice, whereas for some problems it may prove worthwhile to employ exceedingly narrow band filters to reveal significant detail such as fine lines in the spectrum. In general each problem has its own filter requirements and the acoustician should be prepared to use a variety of filters in the exploratory phases of a problem.

If the sounds are transient in character, or if they vary in composition even rather slowly with time, it is highly desirable to conduct the frequency analysis so as to reveal these fluctuations. This art has been intensively used in geophysical exploration and has already been discussed by Dr. Raitt. There the usual technique has been to employ a multichannel amplifier with band pass filters so chosen as to reveal the significant details of the spectrum for the particular problem. Recording is commonly done with a multichannel oscillographic camera. In some instances sufficient information can be recorded with direct recorders using pen and ink or heat or spark techniques. After trying all three of these techniques we tend to prefer the heat recorders where photographic recording is not required, since the hot wire pens are less of a maintenance problem than the pen and ink. However, good results with spark recorders have been obtained recently.

The sound spectrograph developed at the Bell Telephone Laboratories and produced by the Kay Electric Company as the Sonagraph and Vibralyzer are somewhat in a class by themselves as analysis tools for revealing the detailed variations in the spectrum of a sound with time. While the importance of these instruments to underwater sound analysis merits a detailed description, the basic design is thoroughly described in the literature (Koenig, 1946). The commercial units are designed to cover in some detail the frequency region from 2.5 cps to 8800 cps in several steps. The length of the sound sampling analyzed in one recording varies inversely with the extent of the frequency range from 2.4 to 20 seconds. The available frequency range can readily be extended by playing the original record at multiples or sub-multiples of its normal recording speed. The time variation of the spectrum is presented as relative blackening on a spark recording paper. This qualitative presentation is supplemented by a function of the instrument which presents the spectrum quantitatively at any chosen time. It has not proven difficult to supplement the basic circuitry to provide a function which takes the average spectrum over a time interval whose length may be continuously varied over a considerable range.

In the year and a half we have been using these analyzers they have proven extremely useful in revealing frequency effects in shallow water transmission, bottom reflection phenomena and biological sounds. In passive listening the sound spectrogram appears to have the same sort of range of usefulness it has in the visible speech analyses of the Bell Telephone Laboratories, and for much the same reason; they provide an objective basis for comparing the quality of sounds. The spectrogram will be especially useful in identifying biological sounds. In most cases the animals are not identified and it is often difficult to reconcile the descriptions of these sounds made by different observers.

This technique should go a long way toward providing a satisfactory means for comparing observations taken at widely different places and times. Other examples of the use of these instruments are cited under other topics below.

## ACOUSTIC RANGING TECHNIQUES

Distances in open water can be measured by acoustic ranging with considerably greater precision than is possible with any other technique. The instrumentation required is exceedingly simple. A sharp transient sound such as an explosion is initiated at one of two points whose separation is to be measured and a listening hydrophone is placed at the other point. The instant of detonation of the explosion, if that is the sound source employed, is either transmitted by radio to the receiving point, or compared very accurately with a break circuit navigation chronometer or with a radio time signal such as from WWV. In this latter case the arrival of the sound at the hydrophone is compared with a similar break circuit chronometer or radio signal at the listening point. If the initial sound is received by radio at the receiving station the acoustic travel time is easily read from a single record at the receiver. If radio time comparison is employed the start of the sound and its arrival can be directly compared simply by comparing the two records. If break circuit chronometers are used than the necessary procedure is to compare both of the chronometers with such a common time base as WWV or carefully compare the chronometers themselves as often as is indicated during the survey. The technique of transmitting the shot instant by radio works well with radio equipment ordinarily available for scientific work at sea only to rather short ranges, say to the order of 50 to 75 miles. At greater ranges it is usually necessary to employ the comparison method. In any case the data provided is the travel time between the two points for some acoustic transmission path. The computation of range from this travel time is exceedingly simple in some instances, i.e., when it is known that the first sound to arrive follows a relatively simple, direct path from the source to the receiver. The distance is obtained simply by multiplying the speed of sound in water by the elapsed time between the start of the sound and its arrival at the hydrophone. In many other cases the situation is considerably complicated by there being many paths over which sound energy will travel and be readily distinguishable by the receiver. Hence it is very important to know the nature of the paths and the sound intensity associated with them as well as their relationship to the direct line distance between the two points. Another complication of the problem may be that low frequency energy will arrive at the hydrophone before higher frequency energy. This means of course that it travelled by a different, more rapid path between the two points. In order to measure range adequately in such a situation it is first of all necessary to understand the transmission properties of the location and, second, to make proper use of filters in the electronic receiving equipment at the receiver in order properly to interpret the acoustic records in terms of distance. It seems quite unnecessary to go into details of the instrumentation required for this sort of use of underwater sound. The receiving hydrophones and amplifiers and indeed the analysis equipment, when any complicated analysis is required, are exactly similar to those described under passive listening techniques. It might be worthwhile to point out that crude ranging gear can be utilized for certain problems where the underwater sound transmission properties are not unduly complicated and the precision of the distance measurement does not have to be very great. The simplest sort of receiver with earphones or a loud speaker and a comparing watch synchronized with a similar timepiece at the sending point may be quite sufficient for obtaining distances precise to within a mile over distances up to easily 20 or 30 miles, and considerably greater under the right circumstances.

## SOUND TRANSMISSION STUDIES

It is evident from the preceding discussion of sound ranging that for the use of acoustics as a survey tool, it is essential to understand the details of sound transmission in the area to be surveyed. Sound transmission studies are also valuable as a means of understanding the physical properties and structure of the sea water itself and of its principal boundaries, the surface and the ocean floor. The subject is involved and has been pursued on a number of levels of complication for various purposes. For instrumentation, attention must be paid to the receiving equipment and the sound source; and for the experimental procedure one must consider the location of both source and receiver in both horizontal separation and depth. Again the instrumentation described under passive listening serves as the receiving equipment in all instances. The particular facet of the transmission problem to be studied determines to a large extent the type of source employed. A great deal of use has been made of underwater explosions as sound sources for studying transmission properties and they are the workhorse of several experienced groups in this field. They have the advantage that the initial sound consists of a very short transient whose pressure-time curve is approximately an exponential and whose spectrum, though far from white, nevertheless contains a considerable amount of energy over a very wide frequency range. Hence TNT is a very important instrument in underwater acoustics. Explosives research during the war, particularly at the Underwater Explosives Research Laboratory at Woods Hole has made a considerable contribution to the art of underwater acoustics by supplying a great deal of detailed information about the properties of shock waves in water. Much of this information is available in the book entitled "Underwater Explosions" by Robert Cole (1948).

In addition to explosives, transducers which are similar to the hydrophones we have already been discussing can be powered by an electronic oscillator and driver to produce intense sound at a single frequency. These are very useful for studying the effect of the environment on transmission in a restricted frequency range. Whenever the needs of the problem at hand are either adequately or best served by single frequency transmissions there are an excellent array of transducers available to cover a wide range of frequencies. However, I feel that the use of single frequencies in a scientific research program on sound transmission is not nearly as fruitful as the use of a source having a complex spectrum. This is because the present need in this field is for an understanding of the relative importance of different environmental factors as a function of frequency and for knowledge of how their effect may vary geographically and seasonally. For this work, explosives or other sound sources having a complex spectrum with appreciable energy distributed over a wide frequency range are direct and economical tools for the job. There is no single complex sound source which is completely satisfactory over this whole range for one reason or another, with the possible exception of explosives. There are various devices such as underwater sirens, electrical sparks discharged under water, certain fuels which can be burned under water and various mechanical devices which expend energy acoustically by a hammer driven by an electric motor beating on a steel diaphragm. All of these devices are moderately intense sound sources and can be used for sound transmission studies. At present there is little published information about complex sound sources. A discussion of some of them in Beranek's "Acoustical Measurements" (Chapter 9) indicates their general properties.

It is important to note in connection with sound transmission studies, particularly where they involve complex sound, that the complete transmission system includes the receiving electronics, the amplifier, the recorder and also any analysis equipment that is used after the recorder. It is very important to understand the response of the whole system to the complex sound at very short distances in order to understand completely the effect of the medium in altering the sound both in intensity and in character. A second equally important problem of the same nature is to know the radiation characteristics of the sound source. Is it non-directional at all frequencies? If not, what are its directional properties? How stable is it? Does it give out sound of the same composition independently of time or of wear on the mechanical parts? Is it subject to breakdowns for which it should be monitored? The facts about explosive sound sources are interesting here.

The selection of the explosive is determined by available supply to a large extent but where possible pentolite should be used for smaller charges, say, of the order of a pound. This is because pentolite requires no booster and hence tends to be more reproducible. For larger charges, boostered TNT is entirely satisfactory. In fact the reproducibility requirements for acoustics are satisfied in most work by boostered TNT, even for small charges, since the lack of reproducibility is of the order of 2 to 5 per cent.

The shape of the charge is not especially critical where spherical waves are desired. Squat cylinders or spherical charges are accurately non-directional, but even such cylindrical shapes as a Mk 4 demolotion block ($\frac{1}{2}$ pound) or a conventional depth charge (300 pounds) are less directional than most so-called non-directional acoustic transducers.

Although the initial shock wave within a range of about 5 miles has a simple, wide Fourier spectrum it is followed by bubble pulses with a Fourier spectrum not expressible in simple analytical form.

The use of such complex sounds introduce transmission complications which must be considered in designing the experiment: the presence of reflecting surfaces causes reflections which make the actual Fourier spectrum at the point of observation vary as a function of range, charge depth and receiver depth, and in the case of echo experiments with the position of the echo target as well; also transmission characteristics vary as a function of frequency, and where these variations are not the object of study due account must be taken of them.

Mechanical sources are subject to wear and tear, but the few I am somewhat familiar with seem to fail acoustically, suddenly and in a manner that can be discerned by an experienced, alert observer. Electronically powered transducers can frequently be monitored acoustically. If this is not feasible, electrical monitoring of the power to the transducer is the best substitute.

## ECHO SOUNDING AND ECHO RANGING

Both echo sounding and echo ranging employ instrumentation of a specialized sort to send out a sound signal which travels through the water to be reflected from the object under study and returned to a receiver. In echo sounding the usual object of study is the shape and depth of the bottom of the ocean. The echo sounder is also used for studying the vertical distribution of marine animals through a study of the Deep Scattering Layer. We now know that the Deep Scattering Layer is far more complicated than is implied by its simple sounding title. This layer may consist of one or several concentrations of sound scatters at various depths. The indication on an ordinary echo sounder of the scattering layer appears as reverberation, and the techniques for observing and analyzing the scattering layer records are somewhat similar to those developed for studying reverberation. As is well known by now, echo ranging was developed for the purpose of locating enemy submarines in wartime. Practical peacetime use of echo ranging has been proposed as a device for locating schools of fish, submerged wrecks that may be a hazard to navigation and as a direct aid to navigation in restricted waters. So far as I am aware, none of these functions has ever been employed in a concentrated, highly developed manner by anyone. The potential of echo ranging as a general research tool in marine biology and later as a practical device for locating fish is perhaps one of the most exciting possibilities for the use of underwater sound today. Several groups in this country and abroad are at work on the problem. Many ideas for instrumentation are undoubtedly being carried out and this particular subject deserves far more detailed attention for the purposes of this symposium than I am now prepared to give it. The typical echo sounder or echo ranger employs a rather high single frequency sound signal which may be radiated from the same transducer which is later to act as the receiver, or the radiator may be an independent transducer, separated a relatively short distance from the receiving transducer. Frequencies commonly used in this equipment range from 10 to 50 kc* depending on the use to which it is put.

The versatility of echo ranging or sounding instruments is such that it is possible with complete confidence to think of research in which echo information, namely the bearing, the distance to the object under study and the character of the returned echo, may be analyzed over very wide limits with appropriate design. For example, echo ranging techniques employing a separate sound source and receiver have been used successfully to measure the back scattered sound from objects as small as a single large prawn at a range of about one meter. On the other extreme, it has been a matter of routine to record reverberation from the scattering layers in open ocean at travel times corresponding to depths of 500 to 1000 fms. below the research vessel. The principal difference between the sort of information achievable in the one case and in the other is that individuals can be distinguished at very short ranges since there the directionality of both the source and the receiver is sufficient whereas at considerably longer ranges the same directional properties cause the sound to be spread out through a considerably larger volume so that back scattering is received simultaneously from many individuals. These directional properties are practical limitations in the gear readily available at the present time.

Commercial echo sounders are available in this country principally from the Raytheon, Bendix, Bludworth Marine, Edo and Minneapolis-Honeywell Companies. Most of the models have built in spark recorders and offer a choice of ranges from about 160 feet to 600 fathoms. They are built for fishermen, yachts and steamers; not for science. Echo sounders of greater depth capabilities are not generally available in this country, but have been designed for naval use or for special surveys such as those carried out by the Coast and Geodetic Survey. While these contribute steadily to our knowledge of deep oceanic bathymetry they are still a far cry from the instrument needed to supply many needs in oceanographic science. For example, all echo sounders are designed to have a total beam width of the order of 30° so as always to point in the general direction of the bottom when mounted on the keel of a rolling ship. As a result such a device becomes a very blunt instrument for delineating the shape of the ocean floor in any but rather shallow depths. Further, in order to keep the required transducer small for even such modest directionality, frequencies well above 10 kc must be used. These frequencies penetrate but a short distance into oceanic sediments and hence are only occasionally useful for mapping the thickness of the sedimentary carpet. Greater resolution of bottom shapes could be achieved by an increase of effective directionality. This in turn would have to be accompanied by a high degree of stability in the orientation of the transducer. This could be achieved quite practically by going to a larger transducer below the ship, not only for increased stability, but also to get it closer to the bottom. Penetration of the bottom can be achieved by employing lower frequencies. It is not impossible to incorporate all these features in a single device. However, it would certainly not be of any present commercial or naval interest, except for the data about the oceans it would produce. It appears to me that its development will have to come from scientific interest and out of research funds, and is a possibility in oceanographic instrumentation which merits serious consideration.

---

* - Since this paper was originally presented the Minneapolis-Honeywell Company has introduced a commercial combination echo ranging and echo sounding device which operates at a considerably higher frequency.

The general theory of scattering from small objects has long demanded that marine scattering be studied with an acoustical system in which the scattering as a function of frequency can be studied in detail. A beginning has been made using an explosive sound source and a broad band directional receiver. Past instrumentation has been exceedingly crude acoustically, and is being developed as research in this field progresses. For analysis, similar techniques have been employed as in passive listening, and here the spectrograph type analyzers have proven very useful. This whole field requires extensive exploration and concomitant development of technique before its full potentialities will be approached. Its use as a research tool in marine biology or a commercial tool for fishing is just beginning. It is an exciting and promising field.

## CONCLUSIONS

In the foregoing I have barely scratched the surface of problems which may be attacked in oceanography with acoustical tools, and I feel that the subject of available acoustical instrumentation has been covered only very sketchily.

Only beginnings have been made in the development of acoustics in oceanographic science. We have relied rather heavily on makeshift acoustical and electronic instrumentation. This picture is gradually changing, but it requires continued emphasis and the interest of competent acousticians and electronics engineers. At present very few thoroughly trained and experienced people are at work in this field -- I should guess less than two dozen acousticians and engineers who are relatively free to contribute to purely scientific research. With this sort of a roster progress can be expected to take place very slowly.

## DISCUSSION: R.J. Christensen

Dr. Hersey has treated comprehensively the philosophy and general technical aspects of acoustic instrumentation. It is my purpose to comment briefly on several specific acoustic tools of limited application to the study of oceanography.

The first is the system devised for air-sea rescue, SOFAR (Sound Fixing And Ranging). This system employs a network of three or more hydrophones installed at an ocean depth near that of minimum acoustic velocity. Ashore monitoring stations, cable-connected to the hydrophones, record the signals received from explosive sources at distances up to several thousand miles.

Dr. Press has already pointed out the usefulness of these SOFAR stations in recording the "T" phase of signals of seismic origin, and Dr. Worzel has discussed the use of reflections of the SOFAR type of signal, in locating sea mounts and other types of lithosphere intrusions into the SOFAR sound channel.

Can the SOFAR installations be readily used to investigate water masses and similar large-scale phenomena also? In part, the answer lies in the ability of the investigator to disentangle the many effects which are integrated into the signal as it proceeds along its transmission path.

Received signals possess fair clues about the total length of path traversed and the direction also may be roughly inferred. However, no profound changes have been observed to occur when the length of the path is increased only by an amount sufficient to place the origin of the explosion from one side of a water mass boundary to the other. In other words, the intermass region between two large and distinct oceanic masses does not leave a large imprint in the signal when the transmission path in the intermass region is relatively short.

Since a high percentage of the transmission time for a SOFAR signal is spent in traversing the part of the ocean below the depth of minimum acoustic velocity, the use of SOFAR for the study of near-surface currents does not appear promising.

The installed SOFAR stations will be useful in studying oceanographic changes only after some reliable correlation is established between just detectible signal variations and measured changes in the physical state of the transmission path. No adequate means is yet available for describing simply the physical state of the path, especially where it traverses several thousand miles.

Echo-ranging equipment with high resolution in the time coordinate is the second acoustic tool to which I invite attention. Occasionally, the equipment presents scattering information from which unusual physical conditions may be inferred. Figure 1, shown through the courtesy of Mr. L. R. Padberg of U.S. Navy Electronics Laboratory, is a reproduction of a scattering record of the type recognized as different from the usual. The abscissa represents time after the emission of a short pulse signal, or the equivalent range from the echo-ranging ship to the scatterers. The ordinate represents the distance the ship moves along its course while taking the scattering observation. The blackness of the trace is indicative of the strength of the signal, the blacker the tracer the higher the strength.

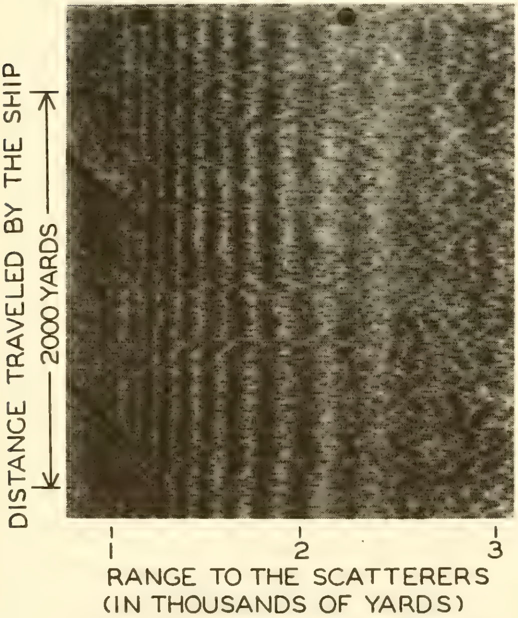


Fig. 1. Chemical recorder trace showing interference patterns resulting from scattering layer.

The light bands which are arranged in striking manner at particular ranges may be explained as a destructive interference in which some of the energy returned by the scatterers arrives via a direct water path and the rest by a path which includes one surface reflection. On the basis of this assumption and from the known geometry and equipment parameters, it is deduced that: the scatters are contained in a plane layer parallel to the ocean surface, the mean depth of the layer is about 300 yards, and the thickness of the layer is probably less than 5 yards. The depth of the ocean at the location was 400 fathoms and reflections from it are ruled out by additional evidence.

This particular phenomenon is found only occasionally. Even at the location of the above observations, it was quite localized. Equipment failure precluded delineation of its boundaries; but it was observed for a distance of 7000 yards along the ship's course, and it was not found at other positions nearby. Some areas display the phenomenon; others do not, apparently. On rare occasions, the interference pattern has been almost circular in shape, indicating a severe distortion of the layer from a plane configuration.

Significant to the purposes of this Symposium is the fact that here is a tool which infers some physical properties of the sea, responsible for the configurations of scatterers which do not appear to be completely explained by biological mechanisms alone.

The measurement of small current velocities existent in the ocean, would appear to be most reliably accomplished by a method utilizing "observation at a distance". Such observation could be made with a high frequency echo-ranging set which senses current velocity as a shift in frequency of sound returned by scatterers within the current. Tests have shown the feasibility of principle, but the packaging and the recording portrayal of the information for general application as an oceanographic instrument will require considerable engineering. Such a device, with little increase in complexity of the basic electronic assembly, could be constructed to give the three coordinate components of the velocity. It appears that measurement of current velocity as low as 0.1 knot would be entirely feasible.

The cross-correlator, a device applicable for precise determination of the time difference of arrival of two signals derived from a broadband frequency source, can be used in the study of underwater acoustic propagation to determine likely transmission paths. The method is most applicable to the case in which there are just several preferred paths. For a continuum of path lengths in which all paths share the energy more or less equally, the method would be of no value except to indicate the existence of such a condition.

Study of the acoustic properties of the ocean bottom, located near the water-bottom interface, can be aided by the use of techniques and devices developed for logging oil wells. Such properties as acoustic velocity, density, and porosity might be so investigated.

## DISCUSSION: H.E. Nash

While the oceanographer and the underwater sound research worker have common interests in both underwater sound and in the ocean, they face these common problems from somewhat different points of view. The oceanographer is interested in underwater sound primarily as a tool which may be utilized to gain greater insight and more detailed knowledge of the ocean, including its boundaries and the life within it. The underwater sound researcher is interested primarily in the manner in which the ocean, its structure, its boundaries, and the life within it affect his ability to transmit and receive intelligence by means of underwater sound.

The general groupings chosen by Dr. Hersey for the framework of his presentation, i.e.: passive listening, acoustic ranging, sound transmission studies and echo ranging and echo sounding, when coupled with applicable laboratory techniques for measurement of the physical properties of the ocean define rather completely the areas of common interest. Like Dr. Hersey I shall confine my remarks to instrumentation for field observations.

One problem in which we have a common interest is the ambient noise of the ocean: its directional properties, its spectrum, and its relation to measurable properties such as wind force or wave height. Since animal sounds are sometimes a predominant factor in the noise background, it is important to know what animals are responsible for what sounds, as well as the seasonal and geographic distributions of these noise sources. I agree wholeheartedly with Dr. Hersey's feelings concerning the value of making magnetic tape recordings during the conduct of passive listening experiments. The possibility of obtaining an objective classification of animal sounds through the use of sound spectrograph techniques is extremely interesting and if successful will remove much speculation from this field.

Dr. Hersey noted that past measurements of ambient noise for the most part have been made with non-directional hydrophones and that the state of knowledge in this field can now be most readily advanced by the use of directional systems. This problem has been examined from a theoretical standpoint by R. J. Urick (1951) under the assumption that deep-water noise is of surface origin and that the radiation from an element of surface area is distributed in angle according to some power, $n$, of the cosine of the angle with the vertical. Determination of $n$, and its dependence on frequency and environmental factors is of considerable interest.

At the Underwater Sound Laboratory we have undertaken to build an electrically steered array to study this problem. The array consisting of thirty-six (36) individual hydrophone elements is shown in Figure 1. The element spacing is slightly less than one-half wavelength at a frequency of 8,000 cps, giving a total length of about ten (10) feet. Each element of the hydrophone is brought through its own pair of leads to a pre-amplifier and compensator which permits the array to be steered electrically from end-fire toward the surface, through the horizontal to end-fire toward the bottom. Compensation or steering of the array is accomplished through the insertion of time delay networks between the adjacent elements of the array so that only signals from a particular direction will add in phase. When no time delay is inserted, the array has its maximum response for signals (or noises) originating in a plane perpendicular to the axis of the line of elements. When a time delay is inserted, equivalent to that required for the acoustic wave to travel in the water a distance equal to the element spacing, the array will have its maximum response along the line of the array. For time delays smaller than this, the line of maximum response generates a cone about the axis of the line array and makes an angle $\theta$ with that axis,

where $\cos \theta = \frac{\tau c}{d}$

$c$ = velocity of sound in water
$d$ = element spacing
$\tau$ = time delay

The method of continuous compensation or steering employed with this array has been described by Holt (1947) and will not be repeated here.

At the half wavelength frequency this array has a directivity index which is independent of the angle to which it is steered. At frequencies lower than that required for half wavelength spacing, the directivity index in the "end-fire" compensated position is approximately 3 db higher than it is for the "broadside" position.

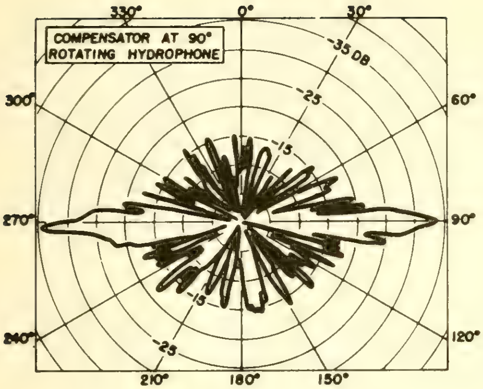


Fig. 2A. 10-foot Line Hydrophone with Compensator at 8 kc.

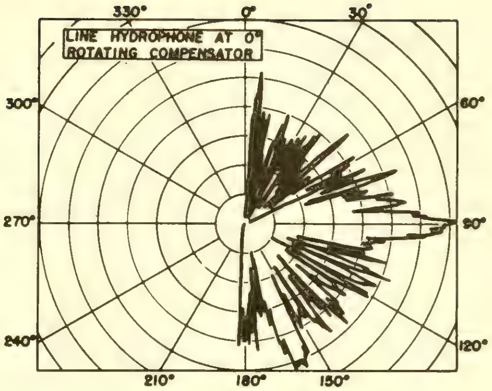


Fig. 2B. 10-foot Line Hydrophone with Compensator at 8 kc.

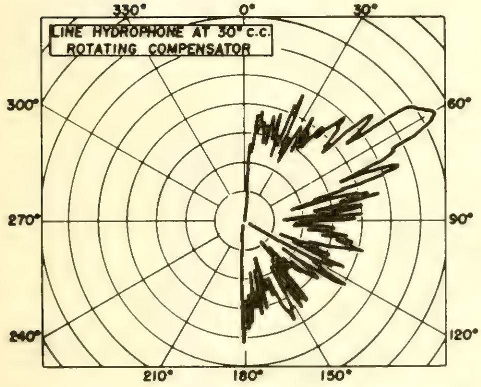


Fig. 2C. 10-foot Line Hydrophone with Compensator at 8 kc.

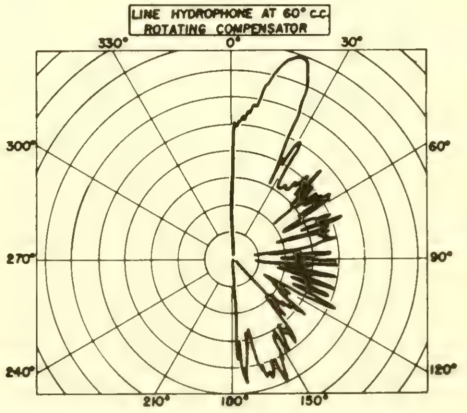


Fig. 2D. 10-foot Line Hydrophone with Compensator at 8 kc.

Directivity patterns for this array are shown in figures 2 and 3. The pattern of figure 2a was taken, with the compensator set at 90° (no delay), by rotating the line array about an axis passing through the center of the array and perpendicular to the line of the array. Figure 2b was obtained by holding the line array fixed and perpendicular to the direction of the signal source. Figures 2c and 2d are compensator patterns taken with the line of the array making an angle of 30° and 60° respectively with the direction of the signal source. The patterns of figure 2 were taken at 8 kc with the source approximately 60 feet from the array.

The patterns of figure 3 were taken at 2.5 kc. For each of these patterns, the compensator was set at a particular angle and the pattern obtained by

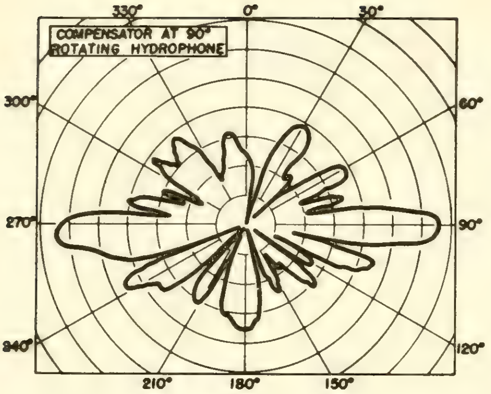


Fig. 3A. 10-foot Line Hydrophone with Compensator at 2.5 kc.

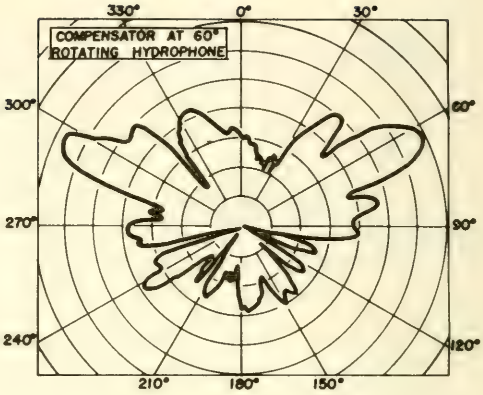


Fig. 3B. 10-foot Line Hydrophone with Compensator at 2.5 kc.

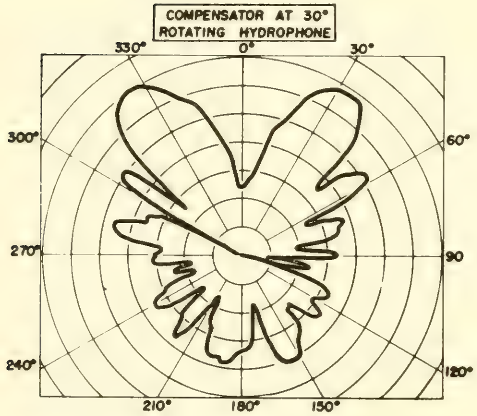


Fig. 3C. 10-foot Line Hydrophone with Compensator at 2.5 kc.

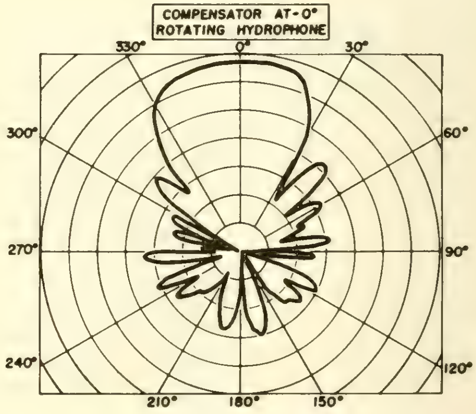


Fig. 3D. 10-foot Line Hydrophone with Comepnsator at 2.5 kc.

rotating the array. Because of the physical symmetry, the full three-dimensional patterns are obtained by rotation of the plane pattern about the $0^{\circ}$ - $180^{\circ}$ axis.

In application the line array is suspended and weighed so that it hangs vertically in the water. Directional patterns are then plotted by means of a polar recorder synchronized with the rotation of the compensator.

Figures 4a and 4b are compensator patterns taken in the field. In figure 4a the sound source is a projector and single frequency generator, while in fig-

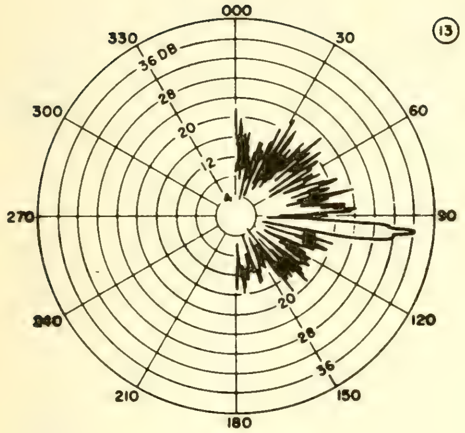


Fig. 4A. Signal from 20-foot Projector Hydrophone at 100 feet Range 12,450 yards.

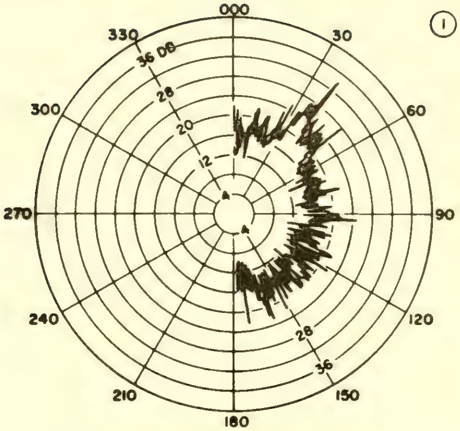


Fig. 4B. Noise-field Hydrohpne at 100 feet Receiver Attenuator at 0 db

ure 4b the directional character of the noise field 100 feet below the measuring ship is depicted. In figure 4b it can be seen that the major noise appears to be coming from a bearing of about 35$^{\circ}$ with the vertical. This corresponds roughly with the location of machinery spaces on the ship from which the measurement was taken.

When utilized from a suitable platform, it is felt that the instrument described will permit an examination of the directional characteristics of noise fields over the frequency range of 1 to 8 kc. Refinements of the instrument should incorporate side lobe suppression even at the expense of somewhat broader directivity patterns.

A somewhat simpler system useful for a study of directional distribution

| | | USS REHOBOTH | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WIND FORCE | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| USS SAN PABLO | 1 | 8 | | | | | | |
| | 2 | 9 | 5 | | | | | |
| | 3 | 12 | 9 | 25 | 2 | | | |
| | 4 | | 15 | 23 | 92 | 23 | 1 | |
| | 5 | | 1 | 5 | 23 | 18 | 7 | |
| | 6 | | | | 1 | 10 | 16 | |
| | 7 | | | | | 2 | 5 | |

Fig. 5A. Simultaneous Wind Force Observations (Beaufort Scale -- Cruise NINE)

| | | USS REHOBOTH | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WIND FORCE | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| USS SAN PABLO | 1 | | | | | | | |
| | 2 | 2 | 11 | 14 | | | | |
| | 3 | 2 | 8 | 37 | 12 | | | |
| | 4 | | 1 | 37 | 63 | 8 | 2 | |
| | 5 | | 1 | 9 | 27 | 29 | 47 | 1 |
| | 6 | | | | 2 | 11 | 19 | 2 |
| | 7 | | | | | | 7 | 4 |

Fig. 5B. Simultaneous Wind Force Observations (Beaufort Scale -- Cruise TEN).

of ambient noise at the lower audio frequencies has been suggested by **C. J. Loda** of the Underwater Sound Laboratory. This system consists of three pairs of equally spaced hydrophones placed along three mutually perpendicular axes (with proper isolation this can be done with four hydrophones rather than six). Each pair is connected in phase opposition so that three mutually perpendicular figure eight patterns are formed. By simultaneous comparison of the signals from the three pairs of hydrophones, information relative to directional distribution within the noise field may be obtained.

The spacing of the hydrophones in each pair is limited to that represented by one-half wavelength at the highest frequency to be used. The lowest usable frequency will be determined by the sensitivity of the hydrophone pair and the receiver noise. Amplification before combination of hydrophone pairs will be necessary if this scheme is to be used when the spacing is very small compared to a half wavelength at the frequency in question.

The Underwater Sound Laboratory has been engaged for a number of years in the collection of underwater sound propagation data, including measurements of reverberation and ambient noise. In order to handle expeditiously the large volume of data being accumulated, it was decided to establish a small IBM calculating unit. While this hardly falls in the realm of underwater sound instrumentation for oceanographic research, the IBM equipment is a tool which has permitted the study of problems which we would not otherwise have considered. In addition to providing a versatile facility for rapid analysis, the IBM installation insures the orderly storage of basic data in a form useful to future investigators.

Having once established such a computing facility, we have found it desirable to give attention to the manner in which data are collected so that they may be most efficiently processed by the machines. Where meter readings are made in the field, the data are recorded on mark sensed IBM cards so that upon return to the Laboratory the machines can immediately be put to work. However, for many applications, photographic film, paper recording tape, or magnetic tape are the most desirable medium for data collection. It was, therefore, necessary to provide for rapid reading and transcription of such records. For this purpose the Underwater Sound Laboratory utilizes a Telereader* and Telecorder.

The Telereader is capable of handling either translucent or opaque records with a maximum width of 12 inches and a minimum width determined by the adequacy of the magnification of 2.5:1 for the record in question. It provides means for accurately measuring distance on the records along two orthogonal axes, permitting rapid and convenient transmission of data from records to digital numbers representing deflections from an arbitrary fixed reference. It incorporates the necessary equipment for supporting and transporting the record; for magnifying and projecting a section of the record, along with the measuring cross wires, on a viewing screen; and for indicating the position of the cross wires by mechanical counters. The Telecorder, in conjunction with an IBM Summary Punch, permits recording of the cross wire positions in standard IBM cards.

The combination of Telereader, Telecorder, and Summary Punch is capable of punching IBM cards at a maximum rate of 50 per minute. With this combination the reproducibility of the measuring system of the Telereader is

---

* - Manufactured by the Telecomputing Corporation, 133 E. Santa Anita Avenue, Burbank, California.

± 0.001 inches.

Since the Telecorder translates voltages into binary digital numbers which are then punched into cards by the Summary Punch, it is possible to use this combination of equipment to record automatically voltage readings on IBM cards. An effort is now being made to determine the usefulness of direct transcription to IBM cards of data originally recorded on magnetic tape.

I would like to comment briefly on the use of instruments in survey operations. The inventor of a given instrument is usually interested in a particular research problem and the instrument which he invents, while in his hands, operates with great precision. Such instruments are usually not satisfactory for use in survey operations where they may be used by relatively unskilled people with no real interest in the results. Consequently, if survey operations are to be successful, instruments must be rugged, simple to use and operate, and capable of producing reliable data in the hands of relatively unskilled operators. In some cases even this may not be enough. For example in figure 5 simultaneous wind force observations taken on two survey ships are plotted for two different cruises. For these observations the two ships were always within fifteen miles of each other and for at least 75% of the observations were within five miles of each other. From figure 5 it can be seen that the wind nearly always blows harder on one ship than on the other.

| | | USS REHOBOTH | | | | |
|---|---|---|---|---|---|---|
| | SEA STATE | 1 | 2 | 3 | 4 | 5 |
| USS SAN PABLO | 1 | 66 | 36 | | | |
| | 2 | 115 | 78 | 18 | 3 | |
| | 3 | 6 | 12 | 38 | 1 | 9 |
| | 4 | | 4 | 1 | 2 | 5 |
| | 5 | | | | | |

Fig. 6A. Simultaneous Sea State Observations (Cruise NINE).

| | | USS REHOBOTH | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SEA STATE | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| USS SAN PABLO | 1 | | | | | | | |
| | 2 | 30 | 23 | 1 | | | | |
| | 3 | 25 | 49 | 30 | | | | |
| | 4 | 22 | 89 | 24 | 17 | | | |
| | 5 | | 7 | 5 | 12 | | | |
| | 6 | | | 5 | 17 | | | |
| | 7 | | | 3 | | | | |

Fig. 6B. Simultaneous Sea State Observations (Cruise TEN).

The anemometer is generally considered to be a rugged, reliable instrument which is easy to operate. However, the spread in the data presented suggests that careful attention must be given to wind force observations when correlations are being sought between this environmental factor and other phenomena.

Figure 6 contains a similar plot of simultaneous sea state observations. The maximum distance between ships was again fifteen miles and for most observations, within five miles. On Cruise 10 Ship A reported sea state 7 three times when Ship B characterized the situation by sea state 3. This situation seems to occur because of the difficulty in judging wave height and separating wave and swell observations. It seems apparent that concentrated attention must be given to the development of instrumentation for more reliable characterization of the surface of the ocean.

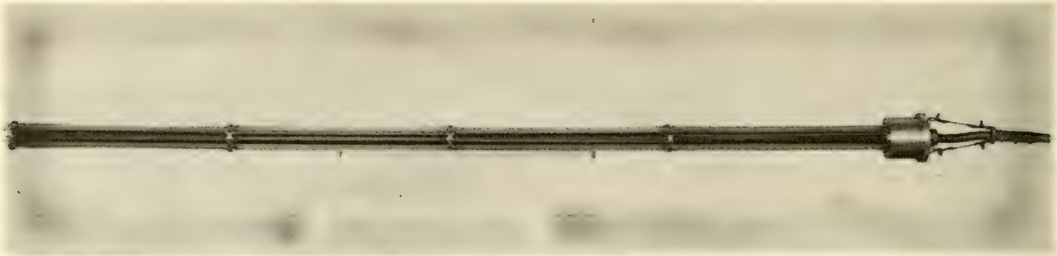


Fig. 7. 10-Foot Line Hydrophone

At the Underwater Sound Laboratory we have encountered certain situations where sound propagation conditions as predicted on the basis of ray theory and the bathythermogram are by no means realized. In these situations a well mixed surface layer was present. Propagation in the surface layer should have been good; it was very poor. In such situations the very great importance of small thermal gradients has been pointed out. It seems entirely possible that under certain conditions current gradients may exist which have an equally important effect. Instrumentation and methods for measurement of current gradient with depth will be welcomed by both the acoustician and the oceanographer.

DISCUSSION: Leonard Liebermann

I believe it is worth pointing out that Dr. Hersey's excellent and comprehensive discussion of "Acoustic Instrumentation for Oceanography" has been presented on the framework of existing acoustic instruments and their applications to oceanography. He has preferred to set the emphasis on acoustic equipment with possible applications, rather than primarily on the oceanography. Suppose instead of this viewpoint, one begins with the important contemporary problems of oceanography; and inquires what contributions, if any, might be made by applying acoustic techniques to these problems. Two major oceanographic problems immediately come to mind: the study of the dynamics of ocean currents and the study of ocean waves and their prediction.

Beginning with the first problem, one of the obstacles to the study of ocean currents is the difficulty with which field observations can be made; the ideal current meter has not yet been invented. However, acoustical techniques make it possible to measure doppler frequencies caused by relatively slow velocities. Hence, it now appears feasible to construct echo ranging equipment designed to measure ocean currents. Comparison of the frequency of the bottom echo with the reverberation frequency from the body of the ocean water would yield the current velocity. In this manner it may actually be possible to delineate ocean currents at different depths. An important advantage would be the possibility of continuous measurements while the ship was under way. The same equipment may also be used for the accurate determination of relative ship's motion.

Another closely related problem is the determination of total water mass flow, in various parts of the ocean. Stommel has made observations on the flow of the Gulf Stream through the Straits of Florida. He observed the induced voltage in a pair of electrodes fixed at opposite sides of the stream. However, his technique is limited in the choice of locations because the two electrodes must be electrically connected; in this case by means of a commercial submarine cable.

Acoustics offers an alternative scheme which does not require a cable. Two hydrophones suspended from two ships would be placed on the bottom, on a line in the direction of the current to be observed. By means of a radio-link, underwater shots would be fired simultaneously (or at a known interval) at the two hydrophone locations. The difference in travel time in the two directions would give the current velocity. For example, if the ships are one mile apart the difference in arrival time is approximately 0.7 milliseconds for each knot of current. Time differences at this range can readily be measured to better than 100 microseconds. If sound transmission paths via several bottom-surface reflections are utilized for the time measurement, the observed current velocity would represent a form of average current from surface to bottom. This observation would probably be most suitable for calculation of the total mass flow. Other sound transmission paths could be selected for additional ocean current information.

Contribution to the study of ocean waves might be made by applying acoustic techniques. Substitution of an inverted echo sounder for the conventional wave meter has already been successfully tried. However, this kind of measurement yields only the time dependent displacement of the sea surface overhead. More important would be an observation of the instantaneous spatial distribution of the waves. Eckart has shown that the spatial distribution of the waves may be characterized statistically by the spatial auto-correlation function of the sea surface. This characteristic function can be obtained in principle by echo-ranging on the sea surface. Choice of echo-ranging frequency would be determined by the period of surface waves of interest. Thus, if surface waves of length 10 feet are of interest, the echo-ranging frequency should be in the neighborhood of 500 cycles.

## REFERENCES: J.B. Hersey

BERANCK, LEO L. 1949. "Aeoustic Measurements". *Wiley, New York.*

COLE, ROBERT H. 1948. "Underwater Explosions". *Princeton Univ. Press. Princeton.*

KOENIG, WALTER and others. 1946. JASA 18 19-49.

## REFERENCES; H. Nash

HOLT, LEE E. "The German Use of Sonic Listening". *JASA 19,4, 678-681 July 1947.*

URICK, R.J. "Some Directional Properties of Deep-water Ambient Noise". *NRL report 3796, Jan,16, 1951.*

# CONSIDERATIONS IN THE CONSTRUCTION OF OCEANOGRAPHIC VESSELS

William V. Kielhorn

## THE NEED

Recently the Office of Naval Research was called upon to furnish the military branch of the Navy with certain oceanographic vessels with which to conduct a program of great urgency. A number of contractors complied with this request, as they always have done in such circumstances, even though it meant the partial curtailment of other highly important contractual work for the Navy Department, and in two cases meant the complete cessation of oceanic investigation for the time being. This brought out very forcefully the need of additional small vessels designed and equipped to conduct these programs which promise to become increasingly urgent within the next few years.

The present oceanographic fleet is a hodge-podge of jury rigs. The Office of Naval Research and the Bureau of Ships have been able to glean from surplus, borrow from non-defense agencies and scrape from the Maritime Commission a few vessels which meet some of the criteria prerequisite for oceanographic work. None of these ships is satisfactory in all respects. Woods Hole Oceanographic Institutions and some of the major universities, such as the University of California, have been able to afford small vessels of their own, but for the most part these are no better than the ships furnished by the Government. In spite of these physical limitations the oceanographic contractors for the Navy have done remarkable well. They have on more than one occasion broken down and had to sail home, making observations enroute. They have lost standing and running rigging and have kept operating. Although most of the research fleet is so limited in speed that the ships are unable to beat out of the way of approaching gales and hurricanes, they have operated in dangerous waters at unfavorable times for the sake of obtaining data which are of direct interest and/or application to naval affairs. The oceanographers have proved themselves deserving of increased confidence and better equipment.

It is the author's opinion that the United States is still far behind in the vital field of oceanography, both in its basic phases and in the resultant naval applications. It seems incongruous that the greatest sea power in the world should have no greater interest in the oceans than do some of the smaller nations, particularly in the field of naval science. It is known from recent Russian translations that the USSR not only has an intense interest in the oceans, but that it has at hand scientists of very high caliber engaged actively in studies of the seas. Great Britain, always a maritime nation, is increasing her efforts in this direction, and the Scandanavian countries are doing likewise, although with more emphasis on economic rather than military oceanography.

The United States Navy has made an effort to divert naval personnel and naval vessels into the fields of basic and applied physical oceanography, but, as shall be pointed out, cannot hope to carry out extensive programs efficiently for several reasons. The Navy has the interest, and the requirement for oceanographic information. Unfortunately, answers to some of its more urgent questions cannot yet be found because there remains a relative paucity of the oceanographic and hydrographic data required to resolve such problems. The need for information is twofold: for hydrographic information which can never be too detailed for naval use, and for oceanographic information both general in nature, much of which we now have, and for detailed investigations that will explain the mechanics of the ocean itself and in its bordering media.

It is especially the need for the latter which concerns us here. This is a problem for approach by the scientific method, not the military method. Resolution of oceanographic problems should rest wholly with those best trained and most aware of what information is required. It remains for the agencies needing the resultant information to furnish the investigators with the finest tools and instruments in the interest of accuracy and efficiency. As any mechanic knows, there is nothing more expensive than a cheap tool. It is not proposed that a cheap tool shall be handed to the contractor with orders to proceed to carry out precision work. On the other hand, it should not be carried to the other extreme by expending funds on a luxury yacht which could be better spent by building two working vessels. A ship is always a compromise between many factors depending upon its proposed use, and thought must be given to the tool, or ship, which will provide the maximum of service for a minimum of cost.

## THE TYPE

What kind of a ship is it that would best suit the needs for the science of the sea? Historic precendents indicate a large, slow ship capable of making extended cruises of two or three years. More recently, there has been a trend towards vessels of more modest size, such as the ketch ATLANTIS. And for other uses, the smaller coastal craft have done noble service.

In this discussion the field will be narrowed down to the category of the small ocean-going ship capable of crossing any ocean, and being able to remain at sea for about two months. The larger vessels may be ruled out, for there is insufficient need of them to warrant building a class of that type. The coastal types may be converted from present day minesweepers, small Coast Guard cutters, or good fishing vessels. This leaves us with the requirement for a unit about 150 feet long and displacing about 600 gross tons. This would be a vessel too expensive for construction by private research organizations, yet not too costly for them to operate. It would be large enough to be equipped with gear and apparatus used in all phases of oceanography, yet it would be small enough to maneuver easily and operate efficiently. It would be long enough to attain the required speed, and it would be comfortable and seaworthy.

The hull of such a ship should be of welded steel, and careful thought would be given to design of space for efficient research and for comfortable living. Mr. William Von Arx has admonished us to give every consideration for comfort compatible with the primary mission of the ship, which would include the complete air-conditioning of all living spaces. The wheel house and chart house must be a little larger than usual, for the latest and best navigational equipment will be used. The radio room may be incorporated into the chart house since there is little or no need for constant radio communication except in special instances. A scientific office and drafting room would occupy the main deck space under and forward of the bridge. The oceanographic laboratory would occupy the deckhouse abaft the smokepipe, and the galley and messing compartment would be forward of the laboratory. The meteorologists should have a balloon inflation shelter on the top of the after deckhouse, and in this shelter could be housed radiosonde and other recording equipment. The belowdecks plan would be dictated to some extent by the required machinery spaces but every effort should be made to keep living quarters clear of the extreme ends of the ship. The acoustics laboratory should be below decks and near the site of the main acoustical equipment.

It is considered that twin screws are a necessity. They should be made of cast steel and should be protected by Kort Nozzles both to increase efficiency and to help prevent fouling. An oversize rudder would be required to maintain control at very low speeds. Both rudder and engine controls should be provided with remote control from the quarter-deck or from the after end of the deckhouse where visibility is best. It has been suggested that the main decking be constructed like a carrier's so that there are many tie-down cleats available yet having a minimum of protrusions.

Dr. Iselin of the Woods Hole Oceanographic Institution has stated that acoustical characteristics of the ship must be thoroughly considered inasmuch as the ship would undoubtedly be used for measurements of sound in the sea, as well as for other oceanographic purposes. He believes that there is a good possibility that a vessel may be designed for both oceanographic and acoustical research purposes, but that if the oceanographic ship does not possess adequate characteristics, one of which is quietness, then another special vessel must be designed specifically for acoustical research.

There is no reason to believe that the acoustician's criteria cannot be met with the oceanographer's in the same design provided knowledge of the requirements is presented before the initial design stages. The acoustics research people particularly desire quietness of machinery. This means consideration of main propulsion and auxiliary machinery giving a minimum of vibration.

Mr. Allyn C. Vine, also of Woods Hole, has requested that the design be quite radical and that at least 80 percent of the available deck space be reserved for the use of the scientists rather than for ship's operations. He, as well as Mr. John Lyman of the U.S. Navy Hydrographic Office and others, is a strong proponent of having an internal well incorporated into the design. Internal wells mean difficulties in design and construction but they have been used successfully in smaller ships and their advantages may far outweight the difficulties. Obviously, the ship must be extraordinarily maneuverable if an internal well is to be used, and twin screws, jets, cycloidal propellers or other aids to maneuverability must be considered. It is the general consensus that no provision whatsoever should be made for placement of guns in time of war except perhaps for the lightest defensive armament.

Internal communications should be very well planned. The familiar "squawk-boxes" should be tied in to each other from all scientific and operational stations aboard, and should have provision for three or four-way conversations without having to hold down keys manually. It is felt that an adequate intracommunication system is highly important for the sake of efficiency, particularly when engaged in multiple-ship operations where the word may be passed by radio to any or all stations on other ships so equipped, and still without carrying additional radio transmitters and receivers at each station. Radio relay through an intracommunication system appears to be the answer.

## THE MAIN ENGINE

a. Direct Reversible Diesel:
The direct reversible diesel engine offers much promise for the small ship. It requires a minimum of engine space, is easily tended by a minimum crew, and is quite reliable and economical. On the other hand, it offers two distinct disadvantages: its speed cannot be reduced beyond a certain point and it subjects the ship to considerable vibration.

b. Diesel-Electric:
This type of machinery overcomes the objections of the direct diesel in regard to flexibility, but the vibration considerations remain; and it is therefore not suitable for the present design.

c. Reciprocating Steam:
Reciprocating steam engines offer great advantages in flexibility and in simplicity. Steam engineers acquainted with this kind of machinery are available all over the world and repairs may be effected in almost any seaport. It does offer the disadvantage of having two separate machinery spaces and it is generally noisy and dirty.

d. Steam Turbine:
The steam turbine is a comparatively efficient engine, especially when using very high temperatures and pressures. It is not as flexible as the "knee-action" steam just described but it is much cleaner and smoother in operation. As in the case of any steam propulsion, two engine spaces are required. This type cannot be considered beof its inflexible nature.

e. Turbo-Electric:
The efficiency of the steam turbine combined with the great flexibility of electric engines points to a Turbo-electric system as the most preferable. It may be made quiet, powerful, light and relatively small. It suffers some from the higher frequency vibrations but these may be fairly well dampened. It also requires a separate fireroom but the tremendous advantages of the combination of steam and electricity outweight the disadvantages.

Steam is a necessity. It means drinking water and showers for the crew, lightweight power for auxiliary machinery and great flexibility with constant-tension features for deck machinery.

## AUXILIARY MACHINERY

The research ship requires auxiliary power comparable to that required for a warship of about the same size. Generators are needed to furnish approximately 120 KW of auxiliary electrical power and this power must be distributed among several voltages both A.C. and D.C. The distribution is dependent upon the design of the motors for the several winches, radios, air-conditioners, reefers, etc.

It is suggested that the auxiliary generators be driven by small high-pressure steam turbines which are fed from steam from the main boilers. At least one small generator should be diesel-driven and backed by a bank of batteries.

Low-pressure steam should be used to operate some of the deck machinery, for the whistle and siren, general heating systems and for the steering engine.

## PERFORMANCE AND DESIGN SPECIFICATIONS

The following approximate performance and design specifications are considered optimum for the purpose for which the ship is designed:

| | |
|---|---|
| Length: | 140 to 160 feet |
| Beam: | 28 to 35 feet |
| Draft: | 12 to 15 feet |
| Speed: | 16 Kn max 12.5 Kn cruise |
| Range: | 4,000 - 10,000 miles |
| Crew: | 15 |
| Scientists: | 12 |
| Food: | 60 days |

It should be noted that these specifications require a maximum speed of 16 knots. There have been dissenting opinions from a few sources that state that 15 or 16 knots is more than is necessary. It must be pointed out that in the modern concept of oceanography the trend is to approach a more nearly synoptic situation, particularly in the study of relatively small-scale phenomena, and therefore speed is necessary. Furthermore, the waste time between stations and between ports of call can be reduced, and the increased expenditure of fuel does not balance in cost the wasted salaries in travel time. But of even greater importance the ship which can steam at 15 or 16 knots would have the power to beat its way out of the paths of severe storms, and would be able to claw off a lee shore should that emergency arise, whereas an underpowered vessel might be in a dangerous situation under the same circumstances.

With comparatively broad beam, the proposed draft seems a little too great for conventional design, but design incorporating a deep keel should be attempted in the interest of good sea-keeping qualities for the reduction of the tendency to pound and to reduce the rate of wind-drift when lying-to in a seaway. Rolling chocks are a nuisance unless they are neatly faired to prevent fouling of wire and overside gear, but they should be used in the interest of comfort, and to increase the directional stability as well as reduce the degree and rate of roll.

## OCEANOGRAPHIC EQUIPMENT

Installation of oceanographic equipment will vary in different areas and at different times, depending upon the investigations to be undertaken, and also upon the development of new and better equipment from time to time. There are a few basic instruments which are common to all ocean-going oceanographic ships. These include apparatus for use in physical, geological, chemical and biological oceanography. A brief description of some of the major items of equipment which should be common to all of such ships is presented below as the gear of primary consideration in design of deck and laboratory space.

Deep-sea Winches - At the present time there is but a single deep-sea whinch in this country, and this winch is still in the design and initial construction phases*. It is to consist of a large winding machine on deck, and a suitable storage reel below decks. Electro-hydraulic power is to be so designed as to be able to handle at least 30,000 feet of step-tapered steel cable. There is difference of opinion as to whether the winch should be located forward or aft. The Navy's SAN PABLO and REHOBOTH have their somewhat smaller winches mounted aft, and with them have been able to anchor successfully in well over 2000 fathoms of water. But winches take up valuable space and in addition placement aft requires that the ship's stern be presented to the sea when anchored. This is not particularly desirable when freeboard aft is to be kept at a minimum. Mr. Martin Pollak and others are strongly in favor of making space available forward for this purpose although this too means inconvenience when handling long, heavy coring devices. Placement forward also precludes use of the winch and wire for towing purposes but this difficulty may be partially overcome by having a smaller unit handling smaller wire of shorter length mounted aft. Most oceanographers are in favor of mounting two winches in this manner.

---

* - Editor's note: This winch has since been installed and successfully used on the SPENCER F. BAIRD, operated by the Scripps Institution of Oceanography.

Hydrographic Winches - The hydrographic winches are rapidly becoming standardized to the electro-hydraulic, self-accumulating type capable of handling about 6000 meters of 5/32"cable. These units are becoming progressively smaller as designs improve and there should be no particular weight or space problems for mounting such units either topside or internally.

Other Winches - Other winches include at least two bathythermograph winches having variable-speed controls and a winch for the geomagnetic electrokinetograph cable. In addition to these there should be one winch forward for handling acoustic gear to the depth of the permanent thermocline and a number of steam-operated gypsys and windlasses spotted about the decks for handling miscellaneous running rigging. In any event, the ship must be equipped to handle nets, trawls, dredges, coring tubes, cameras and samplers of all kinds at any depths.

## CONTROL OF THE SHIPS

It has been stated that the ships should be sponsored by the governmental agencies most needing the results of oceanic research. But they should be operated in the most efficient manner and must be free from severe operational and scientific limitations. The Navy finds it difficult to operate research vessels efficiently because it is usually bound by military requirements and administrative procedures which are not amenable to scientific research. Furthermore, the Navy does not possess in its officer or civilian scientific corps personnel of appropriate experience in sufficient numbers to carry out many phases of oceanographic research. Many of the major talents in oceanography are located in private establishments and in a few universities and this will always be the case. However, they have never failed to attack military problems to the utmost of their ability when such have been presented to them by the Government and in numerous cases they have brought to light military needs of which the governmental agencies were not aware.

Operation of research vessels by the private establishments provides an economic advantage to the Government in still another respect. In the universities of the world and in most of the research institutions there is the traditional inexpensive labor known as the graduate student system. They are students of ability and enthusiasm who will work long hard hours for what amounts to a pittance. Under the guidance of the nation's leading oceanographers these students provide much of the data of the present and most of the knowledge of the future in the science of oceanography. It is a good deal for the Government.

Therefore there can be no doubt that the actual operation of some of the research ships should be done by non-profit institutions who have proven their ability to originate and solve many military problems. In view of the wider variety of their research experience it would seem particularly wise to have them operate the prototype research vessel.

## CONCLUSIONS

In view of the foregoing considerations it is recommended that construction of seagoing oceanographic vessels to investigate new designs which would lead to increased efficiency in the accumulation of knowledge concerning the oceans. These designs should incorporate features of seaworthiness and utility and should contain provisions for the efficient pursuance of physical, chemical, biological and geological oceanography and their closely related sciences.

## DISCUSSION: John Lyman

The following observations pertain directly to the features considered desirable in a vessel of about 150 feet in length, the size proposed by Mr. Kielhorn. The basic principles of design could probably be retained in smaller vessels, down to perhaps 90 feet in length, should budgetary considerations make a smaller vessel more suitable.

## GENERAL CHARACTERISTICS

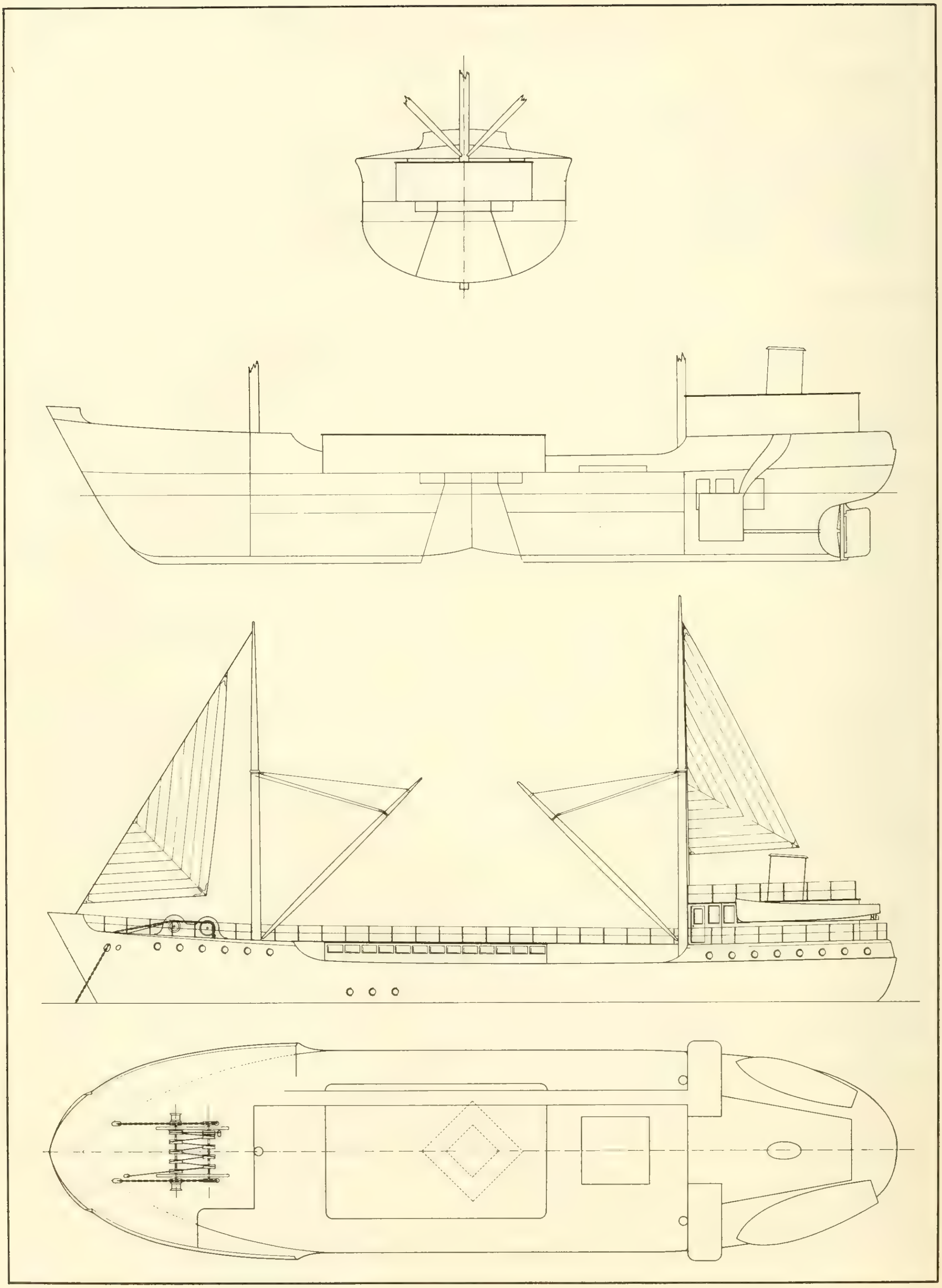
The ability efficiently to conduct various types of oceanographic investigations at sea is in itself a military characteristic of fundamental importance, and should not be compromised to include any other function, such as carrying an armament, training, patrol duty, minesweeping, or picket duty. Indeed, one might even go so far as to suggest that some care should be used in preparing the design of an oceanographic vessel to avoid features that would facilitate conversion to other duty.

The military characteristics of an oceanographic vessel therefore are precisely the characteristics that are best suited to her employment as an oceanographic vessel. Mr. Kielhorn's proposed design, while it undoubtedly would produce a seaworthy, easily handled vessel with comfortable quarters and ample power, would not particularly be suitable for oceanographic duties. The most desirable parts of his ship are occupied by the bridge and engine-room while the oceanographers are relegated to the fan-tail, and must lower their gear in close proximity to the shafts, rudder, and screws.

Figure 1 constitutes the outline sketches of a design in which the maximum number of qualities useful in an oceanographic vessel have been incorporated without particular regard to other features traditional in naval vessels. The result, frankly, is a vessel bearing a strong resemblance to the "steam schooners" that formely carried lumber on the Pacific Coast. For convenience, we will name her the R/V SUITLAND. Some of the thoughts on which this design is based are the following:

## RIGGING

Instead of the single mast amidships, surmounting a pyramidal superstructure -- a design that grew out of the requirement that a vessel should shoot away a minimum of her own superstructure with her own anit-aircraft arament, the SUITLAND has a foremast with two booms and a goal-post mainmast with two booms. Each boom is $7\frac{1}{2}$-ton capacity, permitting the handling of any load that can be supported by a $\frac{1}{2}$" dia. wire, while a four-point suspension ensures adequate control of even the most awkwardly shaped pieces of apparatus.



The masting arrangement further permits the use of sail, a head-sail to steady the vessel in a seaway with the wind aft, and a trysail for setting when hove to. The main topmast supports radar, aerological instruments, and any equipment required for sampling air up to 22 m. above the waterline. The deck erections are concentrated in the ends of the vessel. Both poop and forecastle head have turtle-backs to reduce taking spray aboard. The wings of the bridge overhang the sides, providing control positions for overside operations.

## SUPERSTRUCTURE

The crew's quarters are forward, in the forecastle. Officer's quarters wardroom, galley, engine room, bridge, and charthouse, and messrooms are aft. The laboratories are on the well deck, amidships, where motion is the least. The scientists' quarters and additional working spaces are on the deck below the laboratory. Portable catwalks from the forecastle to the laboratory and from the laboratory to the poop facilitate fore and aft communication in rough weather.

## DECK

The main deck is without sheer, thereby allowing long pieces of equipment to be stowed and handled without distortion. The waterways are arranged to permit a clear length of 94 ft. to be handled on the port side. The superstructure sacrificed here is gained back on the starboard side. The main hatch is abaft the laboratory. Its coamings are kept low and there is a clear deck space of 36 x 25 ft. where trawls, dredges, and other bulky pieces of equipment can be worked on.

## WINCHES

On the forecastle head the SUITLAND has a combined anchor winch and winding machine, which takes care of mooring lines and the port and starboard anchors and chain. Below is a power drum holding 30,000 feet of tapered wire. This can be led through the winding machine either out a hawsehole forward, or aft over a block on one of the foremast booms, permitting either anchoring in deep water with a LWT anchor, or handling heavy coring equipment over the side. Thus anchoring is carried out at the opposite end of the ship from the screw and rudder, and heavy apparatus is handled in the waist and not over the fan-tail. There is a cargo winch for each boom. The hydrographic winch carries 20,000 feet of 5/32" or 6/32" diameter wire. When samples are desired in deeper water, the heavier wire is used; and spare length of wire, carried on spools in the hold, are spliced on by ship's force to replace losses.

## SOUNDING WELL

Probably the most controversial feature of the SUITLAND is her sounding well. Instead of half-drowning a technician on a sounding platform ("chains") over the side, the work with Nansen bottles and similar equipment is done through a well in the very middle of the vessel. The shape of this well is designed to minimize free liquid surface, to strengthen the vessel to the greatest extent, and to take advantage of the wire angle situations that arise either with the wind abeam or with the ship steaming slowly ahead. In the forward part of the well, moreover, the oscillators of the echo-sounding equipment are mounted in such a way that they can be readily withdrawn for inspection or repairs at sea.

## PROPULSION

The plans of the SUITLAND show her driven by a single screw, turned by a steam reciprocating engine powered by Scotch boilers. This is a power plant considered old-fashioned and inefficient in many respects, but compared with diesel it offers the following advantages:

(1) Low first cost
(2) Low cost and wide availability of fuel
(3) Wide availability of experienced operating personnel, and relatively simple mechanical operation
(4) Low upkeep costs
(5) Wide availability of repair facilities, and minimum requirements for spare parts
(6) Low depreciation. Some oceanographic vessels in service today have had diesel engines replaced up to three times in 15 years.
(7) Flexibility of operation. Low speeds for trawling or station-keeping are being easily accomplished.
(8) Minimized vibration. This is an important point where the work requires use of galvanometers, microscopes, etc. All auxiliary machinery can be turbine-driven.
(9) Availability of distilled water
(10) Availability of steam for operating winches.

To be weighed against these advantages are the greater weight of the installation (which is not such an important problem in a vessel not carrying cargo), lower fuel efficiency, and need for a larger engineroom force. A careful study should be made of union manning scales, Coast Guard requirements, fuel costs, and prevailing wages in the home port before reaching a final decision as to power plant, since conditions may vary with localities.

With regard to the use of a single screw versus twin screws, a reliable power plant needs only the single screw, and the possibility of entangling gear is greatly reduced. In this connection it is pointed out that the Navy, as reported in the May 1952 Bureau of Ships "Journal", has recently settled on single-screw installations for all jobs under 30,000 SHP. Since the SUITLAND is to cruise at 10 knots and have a top speed of 12, her power will be around one-fiftieth of this figure.

## ICE BREAKING ABILITY

In a vessel as small as the SUITLAND, addition of ice navigation features probably represents addition of considerable weight and first cost, and the added weight will be useless 85% or 90% of the time. She will not have the power to be an out-and-out icebreaker; rather, she will be a semi-icebreaker, and there is no such thing as semi-ice. Possession of strengthening will only be an invitation to place the vessel in situations from which she will be unable to extricate herself.

If an oceanographic vessel for work in ice is required, consideration should be given to modifying one of the existing Wind-class ice-breakers and adding the necessary facilities for oceanographic work. Only with a vessel of this tonnage, horsepower, lines, and thickness of plating is there assurance of safe operation in ice.

## DISCUSSION: B.K. Couper

Officially, the Bureau of Ships has no opinion on the subject of the design of an oceanographic vessel, and my presence here cannot be construed as official. Until the construction of a given type and of a particular vessel is approved by Congress the Bureau has no official interest in the ship.

A new design of vessel is added to the construction schedule usually as the result of a defined military requirement. It seems to me personally that the originating of the requirement for an oceanographic research vessel could move faster if initiated powerfully from outside the Bureau of Ships -- perhaps as the recommendation of an agency like the National Research Council, to the Office of Naval Research, and through ONR to the Chief of Naval Operations.

There is much personal interest (within the Navy Department) in newer types of ships. It is important in this case that the right people talk together at the right time.

The alternative of using a private yard for design and construction should not be overlooked. The Government has found it wise to subsidize specialized ship construction because of possible wartime use.

In some respects, such as saving in time, weight and critical materials and avoiding priorities, the commercial construction scheme might be faster and more satisfactory.

But for either Navy or commercial construction, three things are required:

a. A consensus on what is wanted. (Recommended, a committee of one representative each from Woods Hole Oceanographic Institution, Scripps Institution of Oceanography, Office of Naval Research, and one member at large, preferably an expert in the shipping industry.)
b. If Navy-furnished, the operational control must be under proven auspices with a record of previous good operating experience.
c. The proposal's details must be at hand in advance, for use at the most advantageous time for making the proposal.

Finally it is recommended that organized cells of interest be formed to further the symposium's idea on:

1. echo-sounders
2. reversing thermometers
3. oceanographic research vessels

DISCUSSION: Allyn C. Vine

Mr. Kielhorn has certainly opened up a long standing topic for discussion. He has said so little to argue with that all I can do is to approach the same problem with a little different slant.

Before going into details on a research vessel I would like to explain a few of my general thoughts on the construction and operation of a marine research vessel. While you may or may not agree with them they have served as the basis for my thinking.

Conversions will always have their place in oceanographic research and this report is not aimed at eliminating them. It does not, however, seem wise or economical to use nothing but conversions. A good research vessel can serve as an excellent prototype for vessels which industry or the Navy will need for their research or development projects, and can serve as a guide in the conversion of other vessels for research.

I believe that the design of the vessel we are discussing should be called logical rather than radical. A freighter would not be logical if it were not mostly hold nor would a carrier be logical unless it had a big flat deck. A research vessel is as specialized as a merchantman or a warship and only in rare cases is it practical or economical to convert one into the other. Also we must remember that most of the individual features which we are apt to call radical have been successfully used in vessels before, so it is only the combination which is unique.

I do not think our various requirements are particularly contradictory or even so very expensive. They show that the field is broad and that a good research vessel needs to be versatile. Experience has also shown that the versatile ship nearly always has a financial backer while the special-purpose ship is apt to sit at the dock for lack of operating funds.

There are several ways of figuring the cost of a research vessel. The usual one is the cost per year or per day at sea, but I believe a more realistic one would be the cost of a working day, on station, with adequate facilities. I will agree that the former gives the monetary outgo, but the latter determines the scientific income and hence in the long run the monetary income. The days lost when slowed up by storms, by low speed, by breakdowns, by loading, unloading, etc., are just as expensive and far more heartbreaking than the days spent working on station.

The size of the crew is the largest determining factor in the cost of operating a research vessel and hence the design of the vessel should be such as to keep this to a minimum. Fuel is usually cheap compared with food.

The life of a good ship is at least twenty years so even $1,000,000 first cost doesn't look so bad when amortized over a period of 20 years. Surely a vessel designed for the job could do 25 percent more work than existing ships. Another feature is that maintenance costs should be small for the first ten years of a new ship.

At the moment I believe the principal requirement for an oceanographic ship is something a little larger and more versatile than Scripps' ATA, the HORIZON. I say somewhat larger because I believe a vessel of 20 percent greater size could be operated at about the same cost and with the same crew but have nearly twice as much space available for scientific work.

We should not rule out the coastal vessel of 80 to 100 feet because such a vessel could be a great work horse for oceanography. At the moment however, it seems that the need for such a vessel is somewhat less and the design problem is somewhat simpler.

Neither should we rule out the large offshore vessel of say 250 feet that can go off for long trips, fuel smaller vessels, carry its own supplies, machine shop, etc. Such a vessel would permit carrying spare reels of wire, a shore based lab to set up on small islands for a month or so. It could also carry a boat on deck which could work in company with its mother ship. Such a ship could carry and service many buoys. It could have several kinds of laboratories set up on it all the time. Such a vessel need not have a crew of more than 25 or 30 and might be cheaper to operate than two of our present vessels.

However, to return to the all around medium size oceanographic research vessel, I would propose a vessel of about 180 feet long, 30 foot beam, 16 foot draft.

Major features have been pretty well covered in previous papers so I would like to list some of the smaller design features which would greatly facilitate research work. They are not listed in any order of priority and of course other research workers would have additional ideas.

(1) She should have a cruising speed of about 12 knots, probably with diesel power. Her lines should be clean with a minimum number of decks, ladders, etc. Her design should facilitate easy communication and low maintenance. Her deck should be full both aft and forward and the bulk of her main deck should be devoted to science; 40 percent of it to open deck and 40 percent of it to lab space (about 1500 sq. ft. each).

(2) She should have ample deck space to work over the stern and over at least one side. Provision should be made to work off the weather deck if the main deck is too wet. The interior ladders between the bridge, lab and lower lab should be arranged to facilitate communications with the understanding that the ship may often be conned from the lab rather than the bridge.

(3) The best choice of propulsion does not seem to be immediately apparent as several of the types discussed have great merits. A closer look at this problem is required.

(4) I do not know if a center well is the answer, but I believe it might greatly facilitate the handling of gear in rough weather. I would estimate that any device or expedient which will enable a ship to operate in one higher sea state is comparable to doubling the displacement of the vessel as far as working at sea is concerned.

(5) The labs and most of the working decks should have flush pads welded to the decks on 24 or 30 inch spacing. These pads should have non-corrosive 3/4 or 1" threaded inserts so eyebolts or equipment can be installed or moved around easily.

(6) The interior of all labs should be constructed so as to permit the insertion of plywood bulkheads at intervals of every 2 or 2½ feet. The steel framing should be spaced at regular intervals and drilled at regular intervals.

(7) The lab should have doors or hatches which will permit moving completely assembled benches aboard as large as 2 x 6 x 10 feet.

(8) Have the ship's rails almost entirely free from permanent stays. This is to permit leading lines and cables around the decks. Numerous pad eyes, cleats, removable stanchions, etc., should be available on the inboard side of the rails and on the deck houses. The rails should have numerous fittings for special small davits, winches or A-frames. The rails should be 6 to 10 inches wide, flat on top, and should have an easily replaceable oak capping. It should be possible to mount a small davit about every 4 feet along the rail.

(9) Have main frames extend to the rails for reinforcement at possible A-frame or boom locations. Heavy gear should be secured from mast or tops of rails to leave the deck free for work or stowage. Anchors should be carried in hawse pipes.

(10) One pair of goal posts masts should carry an easily accessible observation platform. This platform can also provide space for adjustment and maintenance of radar, flood lights, etc.

(11) Fuel and water should be in double bottoms and built-in tanks. This will concentrate liquids in the ship's corners and free the central portion for labs and living space. An evaporator should be provided to furnish additional water.

(12) Provision should be made for carrying a riding sail aft and it may also be advisable to carry a jib on a forward stay to help steady the

ship or to sail off the wind.

(13) Hold spaces should be located and be of such construction that they can be useful with scientific work such as being of use for a center well or for a large fish tank.

(14) Provision should be made to light most of the decks at night without interfering with the helmsman.

(15) Provison should be made for easily rigging awnings over portion of of the deck.

(16) The ice box and deep freeze spaces should be particularly well built and insulated to permit extended periods of complete shut-down.

(17) A pair of open-ended vertical 24 inch pipes should extend through the ship from the main deck to alongside the keel to permit rapid installation and accessibility of equipment such as sonar.

(18) There should be a minimum of normally used levels on the ship. There should also be a minimum of half-levels which involve climbbing.

(19) The bow and stern should both be as full on deck as practical to permit easy working at the extremities of the ship and to keep the deck area large.

(20) It is very desirable for the ship to have a straightforward, open plan and appearance. This is to improve communications, the moving of equipment, and to reduce upkeep.

(21) Have one of the small boats a small research vessel such as a 38 foot buoy boat equipped with radio, echo-sounder, etc.

(22) About half of the laboratory space should be divided so as to permit small electronic, hydrographic, chemical and biological laboratories and office facilities which should be maintained aboard the vessel at all times. The remainder of the laboratory space should be reasonably open and versatile enough so that it can be arranged to suit the principal requirements of each trip.

(23) The laboratories should have several outlets through ports for electric cables to go outside. One on each side should be at least 6 inches in diameter. Two 1 inch empty conduits should be carried from the main laboratory to both the forward and aft deck spaces. These runways will be for specialized instrument wires. Multiple conductor cables should be installed between junction boxes near scientific spaces.

In summary I would say that in designing a marine research vessel we have three goals:

> One is fairly routine and consists of incorporating as many known desirable features as one can have without cluttering up the ship.
> The second is to build one which can be operated at a reasonable cost.
> The real design challange is to have it maneuverable, seaworthy and able to operate and do research in a higher sea state than any previous vessel of the same size, either civilian or military.

## APPENDIX: Allyn C. Vine*

Fortunately, discussion and design on a research vessel did not stop after the Rancho Sante Fe symposium and the following pages represent an effort to summarize work done during the fourteen months following the symposiium.

---

*-Editorial Note: Because of the interest and importance of Oceanographic vessels the editors asked Mr. Vine to summarize progress since the symposium. This he kindly did.

The Office of Naval Research had the Woods Hole Oceanographic Institution make a pre-design study of research vessels to put existing ideas on paper and to explore further the most logical choices of power plant, ship size, etc. This study was prepared under subcontract by Francis Minot, Director of Marine and Fisheries Engineering and Research Institute of Woods Hole (Minot, 1953). The report not only consolidated much of the previous thinking on research vessels but went much deeper into the economic and architectural reasons for choosing one size vessel over another. Another important aspect of Mr. Minot's report was that it was written by a naval architect for naval architects.

Particular emphasis was placed on the feasibility of quieting the vessel acoustically so it would be much more useful in acoustic experiments. While Mr. Minot did not restrict himself he placed principal emphasis on the size vessel which would permit extensive offshore cruising.

The conclusions and favorable comments on the WHOI report resulted in the Office of Naval Research holding a conference on 14 and 15 October 1953 to discuss research vessels further. The afternoon and evening of the 14th was very informal and consisted mostly of oceanographers who had been at Rancho Sante Fe and for all practical purposes could be considered as a continuation of the symposium. This meeting was especially productive because it showed that the desires of the east coast and west coast oceanographers were complementary rather than divergent.

The formal meeting was held the 15th of October and was attended by some 50 representatives of civilian laboratories, navy laboratories, Bureaus and design desks.

Representatives from the individual design desks in the Navy were prolific with ideas, were extremely cooperative, and assured us of future cooperation. They were equally agreed that if such a vessel were designed it should be designed as a tool for oceanographic research and not be considered as just a ship to try experimental ideas out on. The keen interest of the design people in the technical aspects of the problem was certainly most refreshing and appreciated.

It is somewhat dangerous for one person to summarize the sense of a general conference but I believe it came very close to this: The requirements and desirable features seem to fall into three classes:

(1) The overall general requirements of performance, space and general arrangement. The following tentative figures were proposed for the first round.

| | |
|---|---|
| Speed: | 12-13 knots |
| Range: | 10,000-12,000 miles |
| Days at sea: | 60 |
| Number of scientists: | 12-15 |
| Draft: | 14-18 feet |
| Length and beam: | To be decided |
| Deck space for science: | The after 40 feet of the vessel, plus an open deck on the starboard side of the cabin 8 feet wide and 60 feet fore and aft |
| Laboratory space: | 20 feet by 60 feet on main deck |

| | |
|---|---|
| Plot room off bridge: | About 10 feet by 20 feet |
| Goal post masts and booms: | To carry 10 tons |
| Work boat: | 10 ton size such as a 38 foot buoy boat |
| Explosive stowage: | 10 tons |
| Habitability: | Tropics or Arctic |
| Maneuverability: | As good as practical. Typical requirement, to maintain a zero wire angle |
| Noise and vibration: | As low as practical |
| Electrical background: | Keep electrical system simple and shielded |

The specific requirements of speed, range and space seemed to be fairly modest by conventional military standards. The Bureau of Ships designers believed this was all the information they would want for their initial consideration.

(2) The many small desirable features which need to be incorporated in a final design were considered essential but they were considered as details which should be filled in after the general hull form and size were established.

(3) There were several very interesting major features which might be very valuable but on which further work needed to be done before they could be considered feasible. Typical of these were:
(a) A center well up to 5 x 15 feet in size from the main deck to the keel;
(b) A forward thwartships screw to give extreme maneuverability.
(c) Perhaps the most important new feature seriously discussed was the practicality and potential gain of incorporating anti-roll devices into the ship. It was generally agreed that a 70 percent reduction in roll would greatly increase the effectiveness of a research vessel.

In view of the importance of the problem a steering committee was set up with a representative from each of several laboratories and Navy groups to further the preliminary design of a marine research vessel.

It therefore seems safe to say that the concept of a specially designed research vessel is far along and that the preliminary preparation of such a design is evolving. It must be understood that none of the actions to date involve procurement or even final design of such a vessel. Preliminary design, however, is a desirable and important step and it appears to be progressing.

# WAVE MEASUREMENTS*

F. E. Snodgrass

## INTRODUCTION

Although considerable progress has been made in the development of instruments to measure the height and period of wind waves and swell as they approach the shore, few instruments have been developed to measure other characteristics of these ocean waves or the characteristics of other ocean waves. Exceptions to this have been the development of techniques to measure very short period waves (surface ripples) and very long period waves (tsunami, surf beat, etc.) by the Scripps Institution of Oceanography. Harbor surge recorders developed by the California Institute of Technology also provide an exception. In addition, basic studies have been made toward the development of instruments to measure waves in deep water and to measure wave direction; but no instruments suitable for routine studies were developed.

The purpose of this paper is to review the instruments that have been developed for the measurement of ordinary gravity waves (periods of 1 to 30 seconds) and to suggest possible solutions to other measurement problems that exist today. Only the measurement of ocean waves that generally are of concern to the engineer are discussed. Many other measurements of the sea surface are important, but are considered beyond the scope of this paper.

## WAVE DIRECTION MEASUREMENT

The measurement of wave direction is as important as the measurement of wave height and period, yet comparatively little effort has been made to develop an instrument to obtain this information. Consequently, no instrument has been designed which will measure and record the direction of waves in the open sea. Visual observation of wave direction also has been unsatisfactory. Short period waves generated by local wind often hide the more important ground swell arriving from distant storms. The observer, therefore, will report the direction of the wind chop instead of the swell which is of primary importance.

At the present time wave direction can be determined best through a study of weather maps. The swell will have the direction of the path connecting the fetch area to the shore site while the wind chop will have the direction of the local wind. Several difficulties arise when wave direction is determined from weather maps. First of all, the weather maps may not have sufficient information to locate the fetch areas; this is especially true of storms in the southern hemisphere. In fact, the study of ocean waves is one source of information about the weather in remote areas. A second major difficulty arises when the wave direction is needed at a site that is not exposed to the open sea. The direction of the waves in deep water may be known but the calculation of the wave direction at the site may be difficult, if not impossible.

---

* - Technical Report, University of California, Series 3, Issue 342.

Instruments to sense the direction of sub-surface wave-generated currents have been designed and built as wave direction indicators (Scripps Institution of Oceanography, June 1950) (Isaacs, 1948), but every attempt to analyze the records obtained from the instruments has been unsuccessful. Extensive theoretical studies and field tests have been made of one of these devices, the Rayleigh disk, which indicated that the instrument was unsatisfactory as a wave direction recorder (Beach Erosion Board, 1950). The difficulty encountered when using the Rayleigh disk to indicate wave direction is not necessarily due to the instrument; but rather the difficulty arises when sub-surface currents are used to indicate wave direction.

Sub-surface Current Recorders - Basically, the Rayleigh disk operates by sensing the direction of the horizontal component of the orbital currents. The Rayleigh disk, a round disk free to rotate about one of its diameters on a vertical axis, senses the current direction by aligning itself perpendicular to the current. When acted upon by the orbital currents of an ideal wave system the disk will align itself perpendicular to the plane of the orbit. The disk will remain in one position throughout the wave cycle even though the horizontal component of the orbital current reverses since it is stable regardless of which surface of the disk points upstream. Under laboratory conditions with a single uniform wave system the Rayleigh disk will indicate the wave direction satisfactorily.

If a steady state current flows in addition to the wave-system orbital currents, the disk will seek a positionperpendicular to the vector sum of the instantaneous horizontal components of the two currents. The disk, therefore, will oscillate between the direction of the vector sum of steady state current and the horizontal velocity of the orbital current at the crest of the wave, and the direction of the vector sum of the steady state current and the horizontal velocity of the orbital current at the trough of the wave. The limits of the oscillation will depend upon the relative velocity and direction of the steady state current and the orbital current. Neither the direction of the steady state current nor the direction of the horizontal component of the orbital currents can be determined from the oscillations of the disk without additional information.

The interference pattern produced by two wave systems with different wave directions is that of a short-crested wave system (Fuchs, 1951). The waves cannot be treated as being two-dimensional with the crests extending indefinitely in the third direction and the sub-surface orbital currents do not necessarily lie in a plane perpendicular to the bottom. Instead, the surface waves must be described perpendicular to the wave direction as well as in the wave direction, and the orbital currents must be described by a three-dimensional system. In general, the orbital currents will have components in two planes: (1) a vertical plane parallel to the direction of the short-crested wave propagation and (2) a plane parallel to the bottom. Directly below the center of the crest of a short-crested wave, the orbit will lie within the vertical plane but at the ends of the crest the orbit will lie in a plane parallel to the bottom. The components of the orbital current in the vertical plane tend to align the disk with the wave direction but the components of the orbital current in the horizontal plane tend to cause oscillations or spinning of the disk. A record obtained from a Rayleigh disk acted upon by a short-crested wave system, or by two or more wave systems with different wave directions, generally cannot be analyzed for wave direction.

A record obtained from a Rayleigh disk in the open sea is complicated not only by multiple wave systems, or complex short-crested wave systems, and by various ocean currents, but also by the irregularity of the waves in height and period. Indeed, the analysis of such a record would seem to be impossible, but, being that ocean waves are variable in height, obtaining information about wave direction from sub-surface current recorders is conceivable.

For example, when the disk lies directly below the crest of a large wave the direction indicated should be reasonably close to that of the crest. If the crest were high in comparison to the average being recorded, the instruments necessarily would be located near the center of a short-crested wave and the orbital currents would lie in the vertical plane; also the magnitude of the horizontal component of the orbital current at the wave crest would be large in comparison to normal ocean currents. The wave direction indicated should be reasonably accurate. Selecting the correct time to read the record would require more information than could be obtained directly from the Rayleigh disk record. The record obtained from a pressure type wave recorder near the Rayleigh disk may supply the required information as it would indicate the passage of large waves. Perhaps recording the magnitude of the orbital velocity, as well as the direction, would supply sufficient additional information to enable a reasonable determination of wave direction.

Regarding the instrument, the basic assumption has been made that the Rayleigh disk, or whatever device is used, is capable of indicating the instantaneous direction of the currents without error. The designer of an instrument, therefore, not only must consider the problem discussed above but also must consider the problem of recording the direction of the sub-surface currents without error.

Tripartite Wave Recorders - The method of determining the direction of propagation of microseismic vibrations by timing the arrival of the wave fronts at three seismographs placed in a triangle has been used for a number of years but generally has not proved successful. A technique of checking the reliability of the measured bearing by also computing the velocity of the microseism from the original data, was developed recently at the Naval Research Laboratories (Kammer, 1951). This improved technique of determining the direction of microseismic waves suggests a possible technique of determining ocean wave direction.

By placing three wave recorders in a triangle, with perhaps fifty feet between recorders and timing the arrival of the wave at the three points, the wave direction could be computed. The difficulty with this type of measurement would be that the wave form recorded may not be identical at the three points due to (1) short-crestedness of the waves and (2) transformation of the waves in the direction of propagation. The variation of wave form at the three recorders would cause errors in the computed bearings.

The validity of the bearings might be tested by computing the apparent velocity with which the wave front crosses the three recorders. If variations in the wave form introduce errors in the computed bearing they will also introduce errors in the computed wave velocity. The computed velocity can be checked against the velocity of the wave determined from the wave period and hydrodynamic theory. By considering only the bearings associated with reasonably accurate wave velocities the direction of the waves might also be determined with reasonable accuracy.

## DEEP WATER MEASUREMENTS

The problem of designing instruments to measure ocean waves in deep water (to supply information about waves in the generating area and along the decay path to the shore) never has been solved satisfactorily. The primary difficulty with this measurement problem is that of obtaining a fixed reference against which the surface elevation of the water can be compared. Probably the earliest attempt to measure waves in deep water was by means of delicate aneroid barometers that measured the change in atmospheric pressure as a ship rode over the swells (Gaillard, 1904). In this case an attempt was made to use the atmospheric pressure as a reference. Measurements from submarines, using pressure recorders, and from aircraft, using sensitive echo-type altimeters have also been employed using the craft as a reference.

A more direct approach to the problem of supplying a reference can be found in the studies of floating spar buoy systems. The following pages describe some of the experimental work completed toward the development of spar buoy reference systems and wave recorders that have been used with the spar buoy.

Long Line Damped Spar Buoy - This system employed a floating spar buoy attached to a damping disk by a long wire cable. The cable was 600 feet long, which enabled the damping disk to act in water that was relatively undisturbed by wave action. The variation of buoyancy as a wave passed the buoy caused only a negligible vertical motion of the system. Thus, a reference was established against the water surface elevation could be compared.

Short Line Damped Spar Buoy (Folsom, 1945) - The short line system was developed because of the difficulty of installing and retrieving the long line system. Since the damping disk was acted upon by water moving with the surface waves, there was an appreciable vertical motion of the shore line system. The motion of the buoy was assumed to be the sum of the vertical components of the water particle orbits at the damping disk, and the motion due to the buoyancy variation as the wave passed the spar buoy.

Correction for the Motion of the Spar Buoy (Rauch, 1945) - Equations have been derived to calculate surface wave height when
- (a) the apparent wave height is known (as found by observing the time history of the water surface on the spar buoy), or if
- (b) the sub-surface pressure time history is known (as found by a pressure recorder attached to the bottom of the spar buoy).

These equations account for
- (a) the orbital particle motion at the damping disk,
- (b) the motion of the disk relative to the particle motion,
- (c) the hydrodynamic attenuation of pressure,
- (d) the effect of waves passing over the spar buoy and
- (e) the phase lag of the spar buoy motion relative to the surface wave.

Studies were also made to determine the tilt of the spar buoy for various exposed lengths and for various wind velocities. A 36-foot spar buoy of aluminum tubing (3" od.) weighing 49.2 pounds was attached to a 3-foot damping disk on a short line. Weights were added to the system to expose the buoy to various lengths, and the tilt was measured. Calculations and experiments indicated

---

Editor's Note: Since this paper was presented two significant advances in open-sea wave studies have been developed at Scripps Institution. They are: Willard Bascom's deep-sea instrument station and James Snodgrass' wave-sensing and telemetering unit.

that not more than one-third of the buoy should be exposed: winds of more than 20 miles per hour caused excessive tilt if 10 feet or more of the buoy were exposed.

Wave Recorders Used With The Spar Buoy - A pressure recording instrument was developed by the University of California to provide a record of 10 minutes duration. The total length of time scale was about 30 inches, and the pressure scale was about 10 feet per inch, with a total range of 3 inches. A pressure-actuated stylus made the recording by marking a prepared wax paper located on the periphery of a drum. The drum moved during operation, guided by a helical groove cut into the shaft about which rotation took place. The rate of movement was controlled by a Standard clock mechanism for which the recording drum acted as the driving weight. The rate of fall was 1 inch per turn and a total of 5 turns was made during the recording period. The linear motion of the stylus was controlled from a spring-loaded sylphon bellows exposed directly to variations of the pressure in the water at the level where the instrument was placed. This recorder, called the Mark I Deep Water Wave Recorder, proved to be too delicate, and the records obtained were of insufficient length to provide good sampling for statistical studies.

The Mark II Deep Water Wave Recorder was then constructed using the component parts of a standard bottom mounted wave recorder for use with the spar buoy system to provide records 3 hours in length.

Suspended Underwater Pressure Recorders - Disadvantages of the damped spar buoy system were difficulties of installing and retrieving the long line and large component parts. In order to overcome these difficulties, Rauch and Folsom (Rauch, 1945) suggested a scheme for suspending a pressure recorder from a float that would follow the sea surface. The pressure at the suspended recorder would vary as the recorder was raised and lowered in the water by the surface float. If the recorder were to be suspended more than one-half a wave length below the surface, the pressure fluctuation at the recorder would be equal to the water head through which it was raised. If suspended at a lesser depth the sub-surface pressure fluctuations due to wave actions would have to be considered.

The immersion of the float should be kept constant and the weight of the recorder sufficient to hold the connecting line taut so that the system would operate as a rigid unit. The proper depth for the pressure recording unit would have to be a compromise, since records independent of sub-surface pressure fluctuations require great depths (800 feet or greater for wave periods of about 16 seconds), but convenience of handling required as shallow a depth as possible.

To determine the pressure response for various wave periods, a theoretical investigation was conducted of the dynamics of the system. The response of the recorder was shown to be a function of the depth of the pressure recorder and the period of the wave. Graphs were developed to convert the pressure recorder reading to surface wave height for various wave periods and instrument depths.

Sonic Radio-link Spar Buoy Wave Height Meter (Bureau of Ships, 1948) - Two types of radio-linked spar buoy systems were studied at the U.S. Navy Radio and Sound Laboratories during 1945: (1) a radio-linked buoy that measures the wave height by sonar means and (2) a radio-linked buoy that measures the wave height by a pressure-actuated device. The radio-link was provided to eliminate the need of recovering the instrument to obtain the record. A sonar-type unit was developed and several field experiments were made with this unit. No pressure-actuated type instrument was developed at this time.

A 25-foot spar buoy was made of 4-inch o. d. dural tubing, with the transmitter mounted at one end and the sonic transducer at the other. The transducer was mounted on a bracket at the bottom of the buoy, facing up toward the surface of the water. Pulses of sound energy were radiated from the transducer to obtain the echoes from the surface of the water and also the echoes from two reflectors fastened 5 feet apart along the side of the buoy. The transmitted signal consisted of an initiating pulse, two echoes from reflector pads a known distance apart and an echo from the water surface. The receiver signal was amplified and applied to the unblanking circuit of a synchoronized oscillograph. The oscillograph was then photographed with an oscillographic camera, which converted the spot presentation of the oscilloscope into a continuous strip record.

This system was used successfully on several occasions. Comparison of these readings with moving pictures taken of the waves passing the spar buoy showed the error to be less than 0.2 feet. Although comparatively satisfactory, no further development of this sonic radio-link method of measuring ocean waves has been made since these first tests.

## MEASUREMENT OF LONG PERIOD WAVES

Waves in a storm area form a most irregular pattern, and have a wide range of frequencies (Munk, 1951). Under storm conditions, most of the energy of the waves is concentrated, however, within a relatively narrow range of periods, say from 5 to 9 seconds. After the waves leave the storm area, they travel as swells. Selective attenuation of the shorter periods leads to a gradual shift of the energy maximum toward the longer periods. Thus, due to dispersion and selective attenuation, the most prominent swell from a storm area several thousand miles away has a period of 12 to 16 seconds.

During the last few years, a number of automatic swell-recording instruments have been installed by British and American organizations. These instruments have demonstrated the existence of long forerunners to the swell, with periods up to about 30 seconds.

Four other types of waves have been noticed whose periods are between the wind-generated swell and the tides. These are:

(a) tsunamis, caused by submarine earthquakes or eruptions (popularly known as tidal waves, although they have no relation to tide-producing forces);
(b) seiches, caused by atmospheric variations;
(c) surf beats, related to the fluctuation in height of the incoming wind-generated waves (Munk, 1949); and
(d) harbor surging, the oscillation found in harbors (Knapp, 1951).

Deep Water Mark III Wave Recorder - Hydrodynamic theory indicates that pressure-type instruments installed in water about 600 feet deep will record the long period wave but not the wind-generated waves of 4 to 20 seconds period. The pressure recorder must be installed in depths less than one-half the wave length of the shortest wave to be recorded to experience more than one percent of the total pressure fluctuation generated by the wave at the surface of the water. Thus, recorders installed in deep water will be able to feel pressure variations of only the long period waves and tides.

In 1947, the Mark III, Model 3, deep water shore wave recorder, shortly after its construction by the University of California in 1947, was tested in 600 feet of water at Drakes Bay and near the Farallon Islands (Chinn, 1949). There was considerable difficulty in making the installations, but records were obtained at both places. Tide effects were filtered from the record by a slow leak in the static pressure chamber.

The records obtained did not show pressure variations that could be related to surface waves. The pressure fluctuations were random, without any evident periodicity. Frequently, readings remained above, or below the center line of the chart (indicating an increase or decrease in pressure respectively) for as long as 15 minutes. The readings were erratic and it seemed impossible that the indicated changes in pressure could be caused by waves.

The explanation given for these records was that the random variations were due to pressure changes in the instrument air dome, caused by temperature fluctuations. Temperature changes of only one degree, or less, can cause the sort of variation recorded by this instrument.

Tsunami Recorder (Scripps Institution of Oceanography) - The tsunami recorders developed by the Scripps Institution of Oceanography were installed in shallow water, where pressure fluctuations of waves of all periods were present. Both the short period wind wave and tide pressure fluctuations were removed by means of a tuned hydraulic filter and the remaining long period waves were recorded by a pen recorder.

The Mark I (2-stage) tsunami recorder operated at the end of the Scripps pier from January to August, 1948. This instrument (which is sensitive to waves with frequencies lying between those of the wind-generated swell and the astronomic tides) revealed, during times of high wind waves, the presence of irregular oscillations of several minutes period. These waves were called "surf beat", as they are related to fluctuations in the height of incoming waves.

Waves of 15 to 30-minute periods were also observed and tentatively correlated with meteorological disturbances. These storm "seiches" were largely obscured by the relatively high surf beat. Accordingly, it was decided to retune the circuit to lower frequencies, shifting the period of peak response from 15 to 45 minutes (Mark II, 3-stage).

Two Mark II instruments (Munk, 1948) have been installed, one on the end of the Scripps pier and the other at the end of the municipal pier at Oceanside, California. They differ in minor details of construction, but are designed for identical responses.

## MEASUREMENT OF HEIGHT AND PERIOD OF ORDINARY GRAVITY WAVES

Numerous instruments have been developed throughout the world for recording the height and period of ordinary gravity waves of the ocean. More accurately, these instruments record the time history of the water surface elevation at a point; in the case of pressure-recording type wave gages the surface elevation time history is measured indirectly by recording the variations of pressure at a point below the surface. The wave height and period are defined in terms of the surface variation at this point. Wave height is determined by the amplitude of the surface elevation variation and the wave period is determined by the length of time between successive maximums of the surface elevation.

For most engineering applications the measurement of the surface at a point provides a sufficient description of the sea surface. For many special problems a more complete description of the sea surface may be required. For example, the study of the motion of a ship on the sea surface requires a three-dimensional description of the surface; the study of transformation of waves from short-crested swells offshore to long-crested breakers on the beach also requires more information than given by a single wave recorder.

Two basic types of wave recorders are in use today: (1) the surface-contact type wave recorder and (2) the sub-surface pressure type wave recorder. The first type gage has the advantage that the surface elevation is recorded directly, leaving no doubt as to the time history of the surfaces. The surface-contact type gage has the disadvantage of requiring a supporting structure. Subsurface pressure type gages do not require supporting structures, except for a tripod mount on the bottom, but have the disadvantage that the surface elevation time history cannot be determined exactly. High frequency components of the surface variations are not recorded by pressure type gages, hence some information is lost. At times, however, it is advantageous not to record the high frequency components since they tend to mask low frequency components, such as storm swells.

The mechanical design of wave gages varies widely, depending upon exact purpose of the gage, the type of recorder with which the gage is to be used, and various preferences of the designer. Brief descriptions of several gages therefore will be given as examples of the many gages that have been, or might be, designed. Of the gages described, the Beach Erosion Board Step Resistance Gage, the Woods Hole Shore Wave Recorder (now being built by the Beach Erosion Board) and the University of California Mark IX Shore Wave Recorder are the most extensively used today in the United States.

Beach Erosion Board Step Resistance Gage - The step resistance gage is comprised of a series of electrical contact points (modified spark plugs) installed along a sealed pipe at 0.2-foot intervals (Beach Erosion Board, 1948). The spark plugs are connected to a resistance circuit within the pipe. The gage is attached vertically to a supporting structure (such as a pier) with the bottom of the gage below the lowest expected wave trough; the top of the gage must be above the highest wave crest. The normal length of a step resistance gage is 25 feet.

A constant voltage transformer (115-volt AC) supplies power to the gage; its primary is connected through a timing switch to provide automatic programming. Alternating current is supplied to prevent polarization, and is converted (through a selenium bridge rectifier) to a proportional DC current, which in turn drives the recording unit mechanism. A Brush magnetic pen recorder is used, which has a high frequency response and can record the shortest period wave.

The values of the resistors, connected to the contact points of the gage, are adjusted so that the variation in the current is proportional to the submerged length of the gage. By recording the variation of the gage current, a record of the rise and fall of the sea surface is obtained which includes tide variations as well as wave action. Wind chop and wave form are reproduced accurately, providing the response of the recorder is sufficiently rapid.

a. Series-type step resistance gage: In this type, the resistors are connected in a series circuit, with the junctions between resistors tied to the contact points. As the sea rises, the water shorts all resistors tied to submerged contact points, which causes an increase in current proportional to the number of contacts below the surface.

This instrument is susceptible to current leakage because of the relatively high value of the resistors connected between the contact points. The film of water left on the instrument by the receding water tends to short the resistors connected between the contact points. Because of this, the use of the series-type resistance gage is restricted to measurement in fresh water, where current leakage caused by the water film is negligible.

b. Parallel-type step resistance gage: In this gage, one end of each resistor is connected to a spark plug, the other end to the gage voltage supply. The sea provides a current path between the contact points and a ground rod. The ground rod is then connected to the other side of the voltage source. As the spark plugs are submerged, the resistors are added in parallel. The values of these resistors are so selected that the current flowing in the gage is proportional to the number of contact points submerged.

The parallel-type step resistance gage is not affected as seriously by the accumulation of water film as is the series type, because its resistance values are small compared to the water film resistance. The gage should be used only in salt water because the resistance path between the contact points and the ground rod must be small compared to the resistor value.

c. Portable-type step resistance gage: The size and weight of the step-resistance gages used for permanent installations make temporary installations impractical. A light-weight step resistance gage, 6 feet in length, therefore, has been designed and built by the Beach Erosion Board to fill this need.

Woods Hole Shore Wave Recorder (Klebba, 1945) - Developed by the Woods Hole Oceanographic Institution, the Woods Hole Recorder has a transducer consisting of a coil and magnet (component part of a radio speaker) arranged so that the total magnetic flux linkage of the coil varies as the water pressure fluctuates. The coil is attached to a metal bellows, the length of which varies with the pressure fluctuations. The coil is thereby moved in and out of the magnet, changing the flux linkage.

Recordings of the flux linkage of the coil can be made with a General Electric photo-electric recorder (a direct writing servo-mechanism type recorder) or with the Woods Hole photographic recorder. The Woods Hole recorder provides a record that can be used directly with the frequency analyzer developed at Woods Hole.

The sea pressure acts upon an exposed metal bellows which is compressed according to the total pressure. A second bellows with a small cross section and a light spring constant is coupled through a tube to the exposed bellows; this system is essentially a hydraulic amplifier. Slight movements of the exposed bellows cause large movement of the light bellows to which the flux linkage transducer is coupled. A slow leak around the light bellows prevents the static pressure of the depth and of the tide pressure variations from affecting the position of the light bellows.

Mark IX Shore Wave Recorder (University of California) - The Mark IX system (Snodgrass, 1951) is designed as a general purpose instrument for permanent installations. Its principal component is the Bourns differential pressure potentiometer which is used as the unit transducer. The movement of the pressure-sensitive brass bellows is magnified by a potentiometer-contact lever which (in normal position of zero differential pressure) divides the resistance of the potentiometer windings equally. Variations of differential pressure cause the potentiometer contact arm to move across the potentiometer windings. The position variation of the potentiometer arm is converted to a proportional current by the bridge circuit and is recorded by the recording milliameter.

The low impedance (750 ohms) and high power dissipation (1 watt) of the transducer potentiometer enables the pressure head to be used with practically any type recorder available. An Esterline-Angus recording milliameter connected in a 24-volt Wheatstone bridge circuit, of which the pressure head forms two legs, is used by the University of California as a standard recording system. Other equipment has been designed for use with this system including (1) a telephone telemetering system which provides telemetering over standard telephone circuits, (2) an ordinate distribution analyzer to provide automatic analyses of wave height and (3) an amplifier (now being developed) with a hyperbolic frequency characteristic to convert the pressure record to a surface wave record.

Mark V Shore Wave Recorder (University of California) - The transducer of the Mark V recorder comprises a 32-junction thermopile installed in a gas-filled rubber bellows (Isaacs & Wiegel, 1950). The reference junctions are in thermal contact with the sea through the pressure head case, while the active junctions are in thermal contact with the gas. The pressure fluctuations act upon the bellows to produce temperature fluctuations in the gas which generate voltages through the thermopile. Because of the relatively short thermal time constant of the pressure head, long period pressure variations, such as tides, are ignored by the gage. The shore installation connected to this pressure head is a Leeds and Northrup recording millivolt meter.

The Mark V pressure head is of simple design and inexpensive construction but has the disadvantage of being difficult to calibrate. The pressure head must be calibrated for each wave period and for each depth of water in which it is installed for research work. This pressure head is designed for military applications where a rugged and easily handled unit is required and precise calibration is not important as critical wave heights can be visually related to the signal.

Mark VI Shore Wave Recorder (University of California)- Work on this recorder was prompted by the need for a high frequency response instrument to record sub-surface pressure fluctuations in the surf zone (Snodgrass, 1952). High frequency response was achieved by using (1) a Brush strain gage recorder with flat frequency response to 100 cycles per second and (2) an underwater pressure head with a natural frequency that is correspondingly high.

The pressure head consists of an air-backed brass diaphragm to which strain gages are attached. Elastic deformation of the diaphragm due to the water pressure is measured by 4 strain gages attached to the air-backed surface of the diaphragm, 2 near the rim and 2 near the center. A continuous record is obtained by connecting the strain gage to a Brush strain gage recorder. Unbalance of the strain gage bridge due to the static depth of the water can be neutralized by rebalancing the recorder after the pressure head is installed. The system is then an effective differential pressure recorder which responds to pressure fluctuations generated by the waves.

The strain gage system is not satisfactory as a total pressure recorder (even though the diaphragm is strained according to the total pressure) because of the instability of the recorder's zero setting. Similarly, the recorder cannot be used to record such long period pressure variations as tides, because of the zero drift.

Mark VIII Shore Wave Recorder (Scripps Institution of Oceanography) - This recorder is a differential meter which utilizes axial strain wires to sense the differential pressure between an exposed chamber and a compliant chamber. The pressures in the compliant chamber stabilize at the average pressure by the flow of liquid silicone through a capillary.

The Mark VIII is relatively light, stable, rugged, and is simple to construct and assemble. Lowpass characteristics are easily adjusted. If desired, a flat response from low acoustic frequencies to trans-tidal frequencies is obtainable. The vacuum compliance model is expected to show no effect from water temperature changes.

The measuring unit, a Statham strain gage, is especially adapted for use in this pressure head by the manufacturers, the Statham Laboratories Inc., of Beverly Hills, California.

The calibration has shown a straight-line relationship of pressure to output over the working range. The signal output is 0.2 millivolts per foot of water per 1.5 volts on the bridge. A total of 15 volts can be used on the bridge, resulting in a response of 10 chart inches per foot of pressure on the standard 2-millivolt Speedomax, and a least reading of 0.005 foot of water.

Knapp Bottom Pressure Gage - A bottom pressure gage designed for studying harbor surging was developed and tested at the U.S. Naval Station at Long Beach, California (Knapp, 1951). A Statham strain gage unit, used in connection with a pressure-sensitive bellows, comprises the transducer of the pressure head. Four strain gages in the Statham unit are connected to form a bridge circuit which is attached to the recorder by an electrical cable. A DC voltage is applied to the bridge, and the record is obtained by photographically recording the unbalanced current with a magnetic oscillograph. Any standard strain gage recorder could be used for the recording system.

The gage differs from other pressure gages in that no slow leak is provided to eliminate tide and long period waves. In place of the slow leak, a solenoid valve is installed which is held open while the instrument is being raised or lowered to prevent damaging the pressure-sensing element. Once the instrument is in place, the valve is electrically closed, which seals the reference chamber at an average pressure corresponding to the depth of the water.

## INSTALLATION OF SHORE WAVE RECORDERS

Selecting the Site - The general location of a wave gage depends on the purpose for which it is intended. If data are needed to compile statistical information describing the general wave action along a section of coastline, the gage should be located so that it is well exposed to the open sea. There should be no islands, bars or prominent points to interfere with the waves before they reach the instrument. In this case, the most suitable sites are off long, straight beaches and off exposed points. The wave data obtained from gages exposed to the open sea can be used to estimate the amplitude of waves acting at a particular site along the same section of the coast. Principles of refraction and diffraction of ocean waves can be used to calculate wave height at a particular site providing the wave height, period and direction in deep water, and the contours of the bottom over which the waves must pass to reach the site are known.

Gages installed to study the waves acting at a harbor entrance, at a pier, or along a breakwater should be located near the site. Careful attention should be given to the local refraction to determine the relation between the waves at the gage and the site studied. Often within a few hundred feet a noticeable difference in wave action can be observed. Gages not exposed to the open sea are seldom used in estimating the wave conditions offshore.

Pier-mounted Gages - Piers provide supporting structures from which gages can be installed easily. Unfortunately, piers are seldom built in locations exposed to the sea; rather, they are located in protected regions such as coves, bays, or where sheltered by offshore islands. At the same time piers can be found that provide suitable locations for gages to study local wave action. When piers are available a surface-type gage such as the Beach Erosion Board Step Resistance Gage can be installed which records the actual variation of water surface elevation (Beach Erosion Board, 1948). Surface fluctuations caused by tides and local wind chop are recorded. Pressure-type wave recorders also can be installed easily off piers. By suspending the pressure recorder close to the water surface, pressure records corresponding closely to the surface profile can be obtained. The extent to which the pressure recorder will reproduce the locally-generated short period waves can be controlled by adjusting the depth at which the gage is installed below the surface.

In some locations offshore oil well structures are available to provide mountings for wave gages. One installation has been completed at Cape Henry, Virginia (U.S. Naval Ordnance Laboratory, 1951) in which a step resistance gage was attached to a pile specially driven for the purpose of installing the gage. The pile, 60 feet in length, was driven 25 feet into the sand bottom at a site 2500 feet from shore, where the water depth was 20 feet. The gage was connected by armored cable to recorders located at a shore station.

Surface-type gages, although requiring cleaning at 3 to 4 month intervals, can be operated for several years without major repair. Several pressure-type gages are also available that provide continuous service for at least one year without repair or maintenance. Either type gage should be installed at least 3 pile diameters from the nearest pile.

Tripods For Sub-surface Pressure Gages - Pressure-type gages, supported by small tripods resting on the ocean bottom, provide a practical method of recording the wave action where there are no piers. The tripods vary in design, depending upon the material available, the equipment available for handling the tripod during installation, the size and type of marker buoy to be used, and the size and shape of the pressure head. The two primary requirements of the tripod are as follows:

a. The tripod should have sufficient weight to keep it in place on the bottom. Marker buoys, when acted upon by heavy seas, may exert a considerable overturning force on the tripod, if the marker buoy cable is attached to the top of the tripod. Also, the electrical cable usually attached to the base of the tripod may tend to drag the tripod when the cable is acted upon by longshore currents. Normally, tripods weigh between 250 pounds and 20000 pounds, depending primarily on the marker buoy size and the equipment available for handling the tripod.

b. The tripod should have sufficient height to prevent the "sanding down" of the pressure head; sand movements are known to occur considerable distances offshore, often changing the bottom elevations by several feet. This is especially true of the seasonal movement of sand onshore during the summer months and offshore during the winter months.

The Woods Hole tripod (Woods Hole Oceanographic Institution, 1947) has a special design feature which allows the instrument to be detached from its concrete base in case the unit becomes covered with sand and cannot be lifted without possible breaking of the lifting line. The tripod is made in two parts: a concrete base weighing approximately 300 pounds and a pipe framework which supports the pressure head. A shear pin, whose strength is less than that of the lifting cable but of sufficient strength to lift the concrete base, holds the two halves of the structure together. A lifting line of 3/8" wire rope is attached to the top of the pipe framework and to a marker buoy. If an attempt is made to lift the tripod while it is covered with sand the shear pin will fail and only the pipe framework need be lifted to recover the instrument.

The concrete base of the Woods Hole tripod is provided with a cavity directly below the tripod in which cable can be coiled. A sufficient amount of cable is stored in this cavity to reach the surface of the water, allowing the instrument to be removed without lifting any cable which might also be covered with sand.

Typical tripods used by the Waves Research Group of the University of California are usually 5 to 7 feet in height with the instrument located 4 to 5 feet above the base. Scrap metal or cast concrete blocks are used to increase the tripod weight. The lifting cable is attached between the top of the tripod and a marker buoy.

Marker Buoys For Sub-surface Pressure Gages - In the past, the methods of attaching the lifting line and marker buoy have been very unsatisfactory. Usually the tripod was lowered to the bottom by a 3/8" to 1/2" wire rope and a buoy attached to the lifting line after the tripod was in place on the bottom. To provide working cable to pass over the hoisting frame and attach to the winch, the lifting cable length was normally made twice the depth of the water. Several difficulties arose from this type of installation. The continual working of the cable due to the buoy following the surface waves weakened the cable and eventually caused failure. To reduce this action a small buoy with buoyancy just sufficient to remain afloat under the weight of the cable was used. These small buoys would still break the cable under the action of large waves, especially after several months of exposure of the cable to salt water.

Marker buoys installed according to Coast Guard specifications using chain between the anchor and the buoy, certainly would last a longer time but would require larger boats to make the installation and a larger tripod to serve as an anchor. Typical Coast Guard specifications for a small open-sea type buoy would be as follows: 3rd class special nun buoy, 656 pounds; 3/4" chain; maximum water depth, 14 fathoms; chain length 2½ times water depth; 2000 pounds concrete block anchor. An installation of this type should be serviced once each 6 months (paint buoy and check chain). The chain should last between 1 and 2 years, depending upon the amount of wave action.

Greatest wear of the chain occurs between the links that touch bottom during wave troughs at low tide and the links that are lifted off the bottom during wave crests at high tide. This wear is due to the rotation of each link as it is lifted. Additional chain may be lifted off bottom during storms and high winds, but the percentage of time is small and the wear of these links is not as critical as that wear caused by normal wave action.

By using a chain whose entire length cannot be lifted by the buoy, a relatively small anchor can be used. The anchor serves only to prevent the chain from being dragged along the bottom during large storms. A long chain also prevents any snapping action caused by the buoy lifting all the slack out of the line. This snapping action is probably the greatest cause of cable failure when small, round buoys are used with wire cable lifting lines.

The inconveniences of handling larger anchors, buoys and cable, as normally used by the Coast Guard, have prevented their use. A small, light marker buoy system that is proving to be more satisfactory comprises a short line and a spar-type buoy. The basic idea behind this scheme is to provide a buoy that holds the short line taut at all times to prevent continual working of the line and to prevent failure by snapping action. One such scheme, used by the Beach Erosion Board, employs a wooden spar buoy, approximately 5 feet in length, which is connected to a 3/8" wire cable. The length of the cable is adjusted according to the water depth so that the buoy is exposed only at low tide. A positive net buoyancy is assumed at all times, except possibly during the trough of large waves at low tide.

A second example of the short-line spar buoy scheme is provided by an installation made at Point Pino, California, by the University of California. This system employs a 30-foot metal spar buoy 6 inches in diameter, and a 5-foot length of chain. The chain is connected between the top of a 6-foot, 1500 pound tripod and the buoy. The length of the chain is adjusted so that the top of the buoy is exposed at low tide. A net positive buoyancy exists at all times and is equal to 150 pounds at the connection between the chain and the tripod when the buoy is completely submerged. This installation was checked after five months service and was found to be in good condition; very little wear of the chain had taken place.

The disadvantage of the short-line spar buoy system is twofold: (1) special provisons must be made to lower and lift the instrument and (2) the replacement or cleaning of buoy requires lifting the instrument. The first difficulty is easily overcome. The instrument can be lowered by a separate line attached to the tripod by a hook which will free itself when the instrument reaches bottom. The instrument can be lifted by lowering a chain noose around the buoy to contact the buoy chain near the top of the tripod. When the noose is pulled tight by the lifting line, the two chains inter-link so that the tripod can be raised.

The second disadvantage of the short-line spar buoy system, the inconvenience of lifting the instrument for periodic cleaning of the buoy, cannot be overcome simply. Periodic cleaning must be made to prevent excessive sea growth on the buoy. If the growth is allowed to accumulate, the downward drag force exerted by the motion of the water may be sufficient to overcome the net buoyancy with the result that snapping action could take place.

A third scheme combining the features of the short-line spar buoy type marker and the Coast Guard buoy type marker has been developed. This system utilizes (1) a median size spar buoy (15 feet long, 7 inches in diameter, 149 pounds total weight), (2) a small chain (3/8") connecting the buoy to a section of large chain (1") which acts as a "variable anchor", (3) a lifting chain (3/8") between the 1" chain and the tripod, and (4) a 1200-pound tripod. The buoy size is determined by the amount of chain to be supported, which includes a section of the large chain. The system is designed so that at a -1-foot tide, the buoy is exposed 2 feet; at a +4-foot tide, the buoy is totally submerged. The large chain, therefore, acts as a "variable anchor" in that it reduces the motion of the spar buoy, maintains tension in the buoy chain, and prevents snapping action in the chain.

Installation of Electrical Cables - The installation of the electrical cable between the offshore tripod and the shore station is a relatively simple task under favorable conditions and with proper equipment. Favorable conditions include a straight, sandy beach without reefs, and a sand bottom from the beach to the instrument. Under these conditions an armored cable can be laid along the bottom without anchors or additional protection and little or no cable wear will take place. The cable will quickly "sand down" so that it is not exposed to the turbulent action of the surf zone or to currents that may exist at times parallel to the beach. After a few months the cables usually will be covered by sand to such depths that they cannot be recovered.

The sanding down takes place for two reasons: first, the fluidity of the sand (especially in the surf zone) will allow the cable to settle until it is covered to a depth of a few inches or more; and second, the movement of sand bars, the movement of sand onshore and offshore, and the movement of sand along the shore will alternately undercut and bury the cable until it may be covered to a depth of several feet. During the summer when the sand moves toward the beach, the offshore cable may be very near the sand surface, or actually exposed. Directly under the summer berm on the beach the cable may be buried as much as 10 feet. Conversely, during the winter the cable may be near the sand surface in the surf zone while offshore it may be buried several feet. The cable seldom, if ever, will be exposed along its entire length.

The greatest danger to the cable exists during storms when the waves approach the shore at a sharp angle. The waves may cut a scarp several feet deep which will expose the cable to the turbulence and littoral currents of the surf zone during the storm.

Under favorable conditions the armored cable need be used only to cross the surf zone. Unarmored cable can then be spliced to the armored cable and laid along the bottom to the instrument site. The splice normally does not have the full strength of the cable and care must be taken to prevent tension at this point. Anchoring the cable near the splice will reduce the tension in the splice. An installation of this type was made at Oceanside, California (Wiegel, 1949).

When reefs exist along the beach or the bottom offshore is covered with rock, the cable cannot sand-down and special anchoring of the cable is necessary to hold the cable in place. Anchoring prevents wear of the cable on sharp edges of rocks and prevents excessive tension in the cable due to long lengths of cable being exposed to underwater currents. The problem of rocky bottoms offshore can be dealt with effectively by having a deep-sea diver walk the cable, laying it around and between the rocks and perhaps anchoring the cable periodically with concrete blocks set on top of the cable. No satisfactory technique has been developed for installing cables over reefs in the surf zone.

Installation of Electrical Cables by Small Craft - The length of cable usually installed for a wave recorder varies between 1000 and 5000 feet, depending upon how far offshore the desired depth of water can be found. Cable-laying ships cannot be used economically to install these short lengths of cable. It is, therefore, necessary to use small boats, landing craft or amphibious vehicles to perform this operation. The DUKW is used more often than the other craft since it can be loaded with the cable, driven to the shore site and used to lay the cable in one operation. The remarks which follow apply directly to the use of a DUKW to install the cable, but should also apply in general to the use of any small craft.

Cable-spool holders have been designed to mount 2500-foot spools of armored cable in the cargo compartment of a DUKW. The design includes a foot brake which acts on the rims of the spool to hold tension in the cable as it is being laid. Without the foot brake the spool will spin, due to the weight of the cable hanging in the water, and cable will be unreeled faster than the craft progresses.

By faking the cable (coiling the cable to form a "figure eight"), the cable can be played out without twisting. A full spool of armored cable (2500 feet) can be stowed in the DUKW cargo compartment without difficulty.

The disadvantages of faking cable in the cargo compartment are that (1) there is always a possibility of the cable becoming tangled and a danger to anyone attempting to free such tangles, (2) there is no simple way to hold tension on the cable being laid and the cable tends to uncoil too rapidly and (3) considerable work is involved in unspooling and recoiling the heavy armored cable.

## ANALYSIS OF WAVE RECORDS

Analysis of Wave Records for Wave Height - If individuals are asked to observe ocean waves and to estimate their height, they will usually report that the waves have an "average height" of, for example, 4 feet and that there are occasionally "maximum" waves 6 feet in height. The estimate for average wave height of several observers is reasonably consistent, providing a frame of reference is supplied against which the waves can be compared. The actual meaning of "average wave height" is of primary importance; it represents what individuals see when observing the random fluctuations of the water surface.

Experiments were conducted by the University of California during World War II to determine the meaning of "average height" as reported by untrained personnel. Waves were observed by several persons for a given time interval and each individual estimated the average wave height for that period. During this time period a surface record was made of the height of the individual waves. A comparison of the data indicated that the estimated "average height" was approximately the average height of the highest 1/3 of the waves, rather than the average height of all waves.

The average height of the highest 1/3 of the waves ($H_{1/3}$) is used to describe the height of the waves. This height is know as the "significant wave height". The average height of the highest 1/10 of the waves ($H_{1/10}$) has been used to represent the height of "occasional high waves" as reported by observers. The height of the highest wave ($H_{max}$) during a given interval of time has been reported by some experimenters, while the average height of all waves ($H_{ave}$) has been reported by others.

The ratios between various combinations of $H_{ave}$, $H_{1/3}$, $H_{1/10}$, and $H_{max}$ have been determined by several investigators. The agreement of daily values to the average values of these ratios and the agreement among values determined at widely separated stations indicated that a definite statistical grouping of waves is generated by wind.

Evidence to further substantiate this theory is found in the results of a statistical analysis conducted by R.R. Putz (Putz, 1950) at the University of California, Berkeley. Analysis was made of 25 wave records selected from various localities and made at various times of the year to obtain good sampling. Putz found that the statistical frequency distribution of observed wave height in a 20-minute interval is approximately constant in form and, for a first approximation, requires for its complete description only the determination of a typical height, such as the "characteristic wave height". The wave height distributions of all 25 pressure records matched, with reasonable accuracy, a Pearson Type III frequency function with a 0.8 positive skewness and exhibited proportionality between the mean and the standard deviations.

Utilizing this mathematical model, Putz computed values for ratios reported. The value of maximum wave height determined from the model was taken as the probable maximum wave in two 20-minute intervals as used by Wiegel in determining his daily maximum wave height. Excellent agreement was found among these four sources as shown in the following table.

| | Computed Ratios | | | | |
|---|---|---|---|---|---|
| | $\frac{H_{1/3}}{H_{ave}}$ | $\frac{H_{1/10}}{H_{1/3}}$ | $\frac{H_{max}}{H_{1/3}}$ | $\frac{H_{max}}{H_{1/10}}$ | Remarks |
| Pt. Arguello, Calif.<br>Wiegel (1949) | | 1.30 | 1.85 | 1.42 | 3 months of data |
| Pt. Sur, Calif.<br>Wiegel (1949) | | 1.27 | 1.85 | 1.46 | 14 months of data |
| Heceta Head, Ore.<br>Wiegel (1949) | | 1.30 | 1.91 | 1.47 | 14 months of data |
| Cuttyhunk, Mass.<br>Seiwell (1949) | 1.57 | | | | 10 months of data |
| Bermuda<br>Seiwell (1949) | 1.57 | | | | 4 months of data |
| Scripps<br>Munk (1944) | 1.49 | | | | 46 waves |
| Average of wave record values | 1.54 | 1.29 | 1.87 | 1.46 | |
| Pearson Type III frequency function Model Putz (1951) | 1.57 | 1.29 | 1.81 | 1.41 | Model based on 25 selected records |

By assuming that a random noise representation adequately describes ocean waves, several statistical properties, including the frequency distribution type referred to above, became evident. One statistical property of the waves is the ordinates of the wave record curve should have a Gaussian distribution; thus, by determining the frequency distribution of the ordinates the Pearson distribution of wave heights can be computed.

An ordinate distribution analysis was constructed which determined the percentage of time the water surface elevation is above a particular height or, in the case of pressure-type gages, the percentage of time the differential pressure exceeds a particular value. Wave information can be channeled to the analyzer by connecting the input terminals directly to the Mark IX Wave Recorder, to the output of the Mark IX Telephone Telemetering Receiver, or to the output of a hand-operated curve tracer. The analyzer determined the percentage of time the curve exceeds 10 different levels simultaneously so that the ordinate distribution is adequately determined by scanning the record once. Each level can be adjusted independently; measurements can be made at desired values according to the amplitude of the record being analyzed.

Twenty-one selected records that Putz used to determine the wave height distribution were re-analyzed by the ordinate analyzer. The data indicated that in practice analysis of the ordinate distribution can be used to determine the characteristic wave height and the complete wave height distribution as determined by measuring individual waves.

Further studies are now in progress to determine the accuracy of this method if fewer levels are measured. The purpose of this study is to investigate the possibility of designing an instrument to analyze and record characteristic wave heights directly. The instrument would measure and record the percentage of time the water surface, or the differential pressure, exceeded a given level. For example, if the water surface elevation exceeded a level of 2 feet (above still water) 10 percent of the time the characteristic wave height theoretically would be $6\frac{1}{2}$ feet.

Reports are now being written at the University of California which describe the ordinate distribution analyzer and the results that have been obtained.

Analysis of Wave Recorders for Wave Period - Wave period has been defined in terms of the time history of the surface elevation at a point location as follows (Folsom, 1948):

> Wave period is the time interval between the appearance at a fixed point of successive wave crests.
> Significant wave period is the average wave period for the well defined series of highest waves observed.

Effectively, the significant wave period is defined as the average wave period of the waves measured to determine the characteristic wave height. The significant wave period as determined from a wave by wave analysis determines the wave period distribution, although not as simply as the characteristic wave height determined the wave height distribution (Putz, 1951).

Fourier analysis of wave records for wave period indicate that the wave period spectrum depends upon the meteorological condition, the age of the waves and the distance the waves have traveled to reach the site. A study of the wave period spectrums obtained from pressure type wave recorders by the Admiralty Research Laboratories, Teddington, England (1947) and later by W.H. Munk (1947) indicated that this type of information was useful in tracking storms at sea and in correlating meteorological and wave data. The analyzers used to obtain the frequency spectrum have been described repeatedly in the literature, so only a brief description of the principle of operation will be given here.

The wave record is fastened to the circumference of a wheel which is rotated at high speed revolving the record past a scanning system. The electrical output of the scanner is passed through a high Q filter to a recording system. As the speed of the wheel is gradually decreased the recorder produces a curve consisting of a series of peaks representing the Fourier amplitude spectrum of the curve on the wave record.

The analysis of wave records by means of the auto-correlation function, and the design of analyzers based on the auto-correlation function, have been investigated by several groups (Seiwell, 1949) (Rudnick, 1949). Although the application of this technique to ocean wave studies is still in the process of development, this method of analysis has proven to be helpful in special problems, such as those involved in the study of transformation of waves and the study of the motion of ships.

The correlogram obtained from an auto-correlation analysis contains information regarding the frequency components presented in the wave record as well as the statistical properties of the record; the correlogram therefore is useful in describing the propagation of waves, predicting of surface waves from sub-surface pressure, predicting the future time history of wave records from the past time history and describing statistical properties of the waves, such as distribution of height and period.

## ANALYSIS OF SUB-SURFACE PRESSURE RECORDS

To obtain the surface wave heights from the pressure record, two factors are required, (1) calibration of the instrument and (2) the pressure response factor relating the sub-surface pressure fluctuations to the surface wave. Thus if

$H$ = wave height at the surface, in feet,
$c_i$ = calibration factor of the instrument, expressed in feet of water pressure per chart division
$K$ = pressure response factor based on the depth of the instrument, the depth of the water and the length, or period, of the wave being recorded, and
$R_i$ = reading of the instrument,

the following equation is used to obtain the surface wave height:

$$H = C_i/K\,(R_i).$$

The calibration factor for most instruments in use today is a constant, which is independent of wave period and depth of the instrument. The instrument provides a record of the pressure variations at the instrument which is accurate in amplitude and wave form.

The relation of the sub-surface pressure fluctuations to the surface wave has been determined theoretically for two-dimensional, irrotational motion of an incompressible fluid in the relatively deep channel of constant depth (Folsom, 1947).

The response factor, K, has been shown to be

$$K = \frac{\cosh 2\pi d/L\,(1-z/d)}{\cosh 2\pi d/L}$$

where

$z$ = depth at which the pressure variation is being measured, in feet,
$d$ = depth of water at the instrument, in feet, and
$L$ = length of the surface wave, in feet.

When $z = d$, the pressure variation is measured at the bottom and equation reduces to

$$K = \frac{1}{\cosh 2\pi d/L}$$

In deep water, where $d/L > 0.5$, and the pressure recorder is located at a distance, D, below the surface of the water, the equation reduces to

$$K = e^{-(2\pi D_i)/L}$$

Pressure records do not enable a direct measurement of wave lengths; the wave length must be calculated from the wave period using the following equation:

$$L = \frac{g}{2\pi}\ T^2 \tanh \frac{2\pi d}{L}$$

where

$T$ = wave period in seconds;

also

$$L = \frac{g}{2\pi} T^2 - 5.12\, T^2 \text{ for } d/L > 0.5$$

Suitable graphs and tables (Wiegel, 1947) have been prepared for the solution of these equations.

Every observer who has simultaneously measured the surface waves and the sub-surface pressure fluctuations has found the surface waves calculated, using the theoretical response factor determined from the above equation, to be too small. Ten random measurements made at the Waterways Experiment Station indicated an average correction of 1.07 should be applied to the calculated wave height. Seventeen laboratory measurements at Berkeley indicated an average correction of 1.10 (Folsom, 1949). Field data reported by the Woods Hole Oceanographic Institute (Seiwell, 1949) indicated a correction in excess of 1.20, while the three sets of field data obtained by the University of California (Folsom, 1946), indicated values of 1.06, 1.08 and 1.18. Recent experiments at Elwood, California, indicated that errors as great as 100 per cent occured when average K factors of a well-defined wave group were used to determine the height of individual waves (Morrison, 1952).

Three sources of error that may cause the discrepancy between theory and experiment are as follows:

a. Loss of information: Due to the hydrodynamic attenuation of the pressure variations, higher frequency components are not present in the pressure records. Observed wave height therefore tends to be greater than wave heights calculated from pressure records.

b. Approximation of wave period: The heights of the surface wave usually are calculated from K factors determined by the characteristic wave period for the record; in some cases the surface waves are calculated from a K factor determined from individual waves, or perhaps each half wave (Putz, 1950). However, all of these methods assume a sinusoidal wave shape and neglect higher frequency components present in the wave form. Thus, even though information is presented in the pressure record, the information is neglected when calculating the surface waves. If a Fourier analysis is made of the pressure record, more information is obtained and a more accurate determination of the surface can be made (Morison, 1952). Greater information is obtained by reading the record at relatively short time intervals. Another technique of computing the surface wave from discreet points employs the application of a "raising kernal" based on a Fourier integral (Fuchs, 1952).

As a further attempt to obtain more information from the pressure record and to compute a more accurate surface wave record, the design of an analog computer is being studied by the University of California. The computer consists primarily of an amplifier with a frequency response characteristic which is the reciprocal of the hydrodynamic attenuation of the water. The desired amplifier would apply a dynamic correction factor equal to $1/K = \cosh 2\pi d/L$ for wave periods assumed to be present in the pressure record.

c. Approximations used in basic wave theory: As stated above, the equations for K factors (relating the sub-surface pressure variations to the surface wave heights) have been derived using two-dimensional theory of waves of infinitesimal height in water of constant depth. The errors introduced by applying these equations to waves of finite height have been investigated (Rauch, 1945) (Barber and Ursell, 1948) and found to be insignificant in the case of bottom-mounted gages. However, for recorders suspended near the surface from piers, errors of 10 percent or more may exist. The effect of a sloping bottom has not been investigated completely. Theroretical studies of short-crested wave systems (Fuchs, 1951) indicates that the K factor computed from the wave period and water depth as given by long-crested wave theory are the same as K factors computed from the short-crested wave theory for the height of the wave directly above the wave recorder.

DISCUSSION: Walter H. Munk

The preceding paper by Snodgrass emphasizes the large effort that has gone into the instrumentation of the 1 to 100 second range. Various combinations of mechanical and electrical devices are well adapted here. I would like to comment, however, on the entire wave spectrum.

Consider the following classification of waves according to wave period as shown in Figure 1.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Period in sec. | $10^{-2}$ | 1 | $10^2$ | $10^4$ | $10^6$ | | $10^8$ |
| | | | minutes | hours | days | months | years |
| Type of waves | capillary | gravity | long-period | | transtidal | | |
| Methods of measurement | optical | electro-mechanical | pneumatic | | numerical | | astronomical |

FIGURE 1

Classification Of Waves According To Wave Periods

This includes wave lengths from a fraction of a millimeter to something of the order of the earth's radius. Details of such a classification have been discussed elsewhere (Munk, 1952).

For periods between 1 and .01 seconds, one obvious method would be to record changes in resistance or capacitance resulting from changes in immersion of thin vertical wires. One difficulty is the hysteresis effect due to water clinging to the wire between wave crests. A more fundamental difficulty has to do with a wake created by the wire itself as the water moves past the wire with the orbital velocity appropriate to the longer waves present. This phenomenon is closely related to the fishline problem. The important periods contained in such a wake will be clustered about the period corresponding to minimum phase velocity, i.e., 0.07 seconds, and this falls right into the range of periods to be measured. For this reason, it seems advisable to avoid altogether any puncturing of the surface. This can be achieved by various optical methods, such as have been used successfully in ripple tanks. There is not particular difficulty in extending optical methods to periods as short as 0.01 seconds. Waves of even shorter periods are so greatly damped by viscous dissipation that I do not think they can be important. But this remains to be seen.

To detect the very low waves with periods between $10^2$ and $10^4$ seconds, it seems advisable to reduce by means of suitable filters the higher swell, and the higher tides which are also present. It is difficult, but not impossible, to obtain sufficiently long time constants by means of electric filters. The difficulty has to do with the leakage of high-capacity condensors. Pneumatic devices work rather well. The "RC-time" of such pneumatic devices, regardless of how the capillaries, air and liquid volumes are connected, and of other plumbing details, varies as $r_p^2 r_c^{-4}$, where $r_p$ and $r_c$ are the radii of the pipes and capillaries used (Munk, 1948). We do not generally desire $r_p$ to be much larger than a foot, nor $r_c$ to be much smaller than a millimeter. These physical limitations place the pneumatic methods in the indicated range of periods.

One difficulty with pneumatic devices is that they become involuntary temperature recorders. The painful fact is that at atmospheric pressure a 1°C temperature change in an enclosed air volume will induce a pressure change equivalent to that exerted by 3 cm of water. At a depth of 300 feet a change by only 0.1°C corresponds to 3 cm of water. For this reason the tsunami recorders at the Scripps Institution have been designed to be temperature compensated, to a first approximation; in addition, they have been placed into a constant-temperature box, and the temperature is recorded for additional control. For periods much longer than $10^4$ seconds the "temperature noise" becomes so large that it would seem better to abandon pneumatic devices altogether.

One obvious method is to subtract the predicted tide. This method should permit the detection of large storm surges with periods between $10^4$ and $10^5$ seconds. Weekly and monthly tide averages have been used, but these contain a rather large tidal residue. Mr. Gordon Groves is devising a more accurate method which appears to be well adapted for wave periods in excess of $10^5$ seconds. The principle is to take hourly water level readings from tide gauges, and to combine these readings in a special manner so as to eliminate the semidiurnal and diurnal tides, but to give nearly full response to other periods. The numerical filter has the following two advantages: it discriminates sharply against the precise periods of the various tidal constituents, making good use of the fact that these periods are known with great accuracy from astronomic observations; and it has the stability that is esential for the study of long-term changes. The calculations can be performed by means of punch cards. In this manner it is hoped that tide gauge records may become a more accurate and accessible tool to oceanographic studies than they have been in the past. It should be noted that the tidal constants are now computed by punchcard methods, so that hourly values are available in suitable form. However, the hourly values are punched manually, and the original recording is still on paper in pencil, much like in Kelvin's day. Is it not possible that the cards be punched automatically at the tide gauges?

For longer-than-annual changes in sea level, the principal difficulty with tide gauge records is that they depend more on the up and down movements of continents than on eustatic changes in sea level. In view of this high "geologic noise" I am not certain whether any reduction of tide records, no matter how painstaking, can give any convincing evidence regarding changes in sea level. Perhaps these very slow oscillations in sea level can best be measured by astronomic means. Changes in sea level due to melting of ice at high latitudes will affect the earth's inertia, and hence its rate of rotation; furthermore, because of the asymmetry of land and sea, the position of the axis of rotation is also changed (Munk and Revelle, in press). These changes can be determined by measurements of astronomic longitude and latitude, respectively. With the accuracy now claimed for both of these measurements it should be possible to detect eustatic changes in sea level by only 1 cm, provided the effect of such changes is not obscured by other, larger effects.

To summarize, starting with short period waves and going toward the longer periods, it appears that optical, electro-mechanical, pneumatic, numerical and astronomical methods seem to be well adapted to cover subsequent ranges of the ocean wave spectrum. Each method extends over a range of periods of about 100:1. These opinions are subject to change without notice.

A word about tides. So far we have considered their elimination by suitable filters in order to study low amplitude oscillations of non-tidal origin in the adjacent portion of the wave spectrum. This should not imply that tides are without interest. To the contrary, recent developments make it seem quite possible that with a determined effort very considerable progress could now be achieved. In the first place, I think that an instrument can now be developed for measuring tides in the open sea. In the second place, it should be possible with the aid of an electronic computer, to obtain numerical solutions to the differential equations of tide generation, subject to the boundary conditions as they actually exist.

DISCUSSION: Carl Eckart

It would be redundant to go further into any of the topics that Mr. Snodgrass has treated, but it occurs to me that it may be profitable to consider the recording tide gauge, which is the ancestor of all wave measuring devices. In age and reliability, this instrument rivals the reversing thermometer. It was well-known seventy years ago.

On March 1, 1882, Lord Kelvin read a paper entitled, "The Tide Gauge, Tidal Harmonic Analyzer and Tide Predicter", before the Institution of Civil Engineers.* Kelvin is perhaps most famous for his abstract formulation of the second law of thermodynamics and his almost equally abstract definition of temperature. It is perhaps not so well-known that he concerned himself with the "nuts and bolts" of instrumentation.

In reading this paper, one should remember that, seventy years ago, precision machine tools were just being perfected, and that these made possible the construction of many ingenious mechanisms that had hitherto been impossible. These ingenious mechanisms fired the popular imagination in much the same way that ingenious electronic circuits do today. In fact, there were many who allowed their enthusiasm for these mechanisms to influence their judgment, just as enthusiasm for electronics is apt to influence judgment today.

In particular, the fountain pen had just been invented, and Kelvin had employed it in his tide predictor. He had been criticized for not also using it in the tide gauge: hence, the following passage from his paper. "The ink-marker ...... has been tried for tide gauges both by the Author and by others, but has hitherto been found unsuccessful, on account of the slowness of the motion, and the long time through which the action has to be continued; and as there is ample driving power in the tide gauge, there is not the strong reason that there is in the tide predicter for preferring the ink-marker to the pencil."

This passage contains what might be called Kelvin's First Law of Oceanographic Instrumentation: There is ample driving power in the sea. It seems to me that all successful and reliable oceanographic instruments capitalize on this. The reversing thermometer has nearly one hundred times the heat capacity of a clinical thermometer, and the bathythermograph probably another thousand times that of the reversing thermometer. Their energy requirements are in these ratios.

---

* - Reprinted in Math. & Phys. Papers, Vol. VI, p. 272, Cambridge (1911).

As a corollary to this principle, vacuum tubes have little place in most oceanographic instruments. Their fields of application are those, like radio and acoustics, where ample driving power is not available in the medium. In oceanography, the ideal of "less than one vacuum tube" can still be approached.

In the discussion that followed Kelvin's paper, the lead pencil apparently came in for further derogatory comment. The Secretary exercised considerable editorial discretion, but by reading between the lines, one can see that some of the gentlemen present were convinced that the fountain pen had rendered the pencil obsolete.

To move the pencil, Kelvin had designed a carriage, moving on a pair of ways, and drawn directly by the wire leading from the float. Apparently, someone doubted the precision of the instrument, which was on exhibit, and suggested a more complicated method of doing this, for Kelvin remarked, "that good workmanship was too often put into requisition to overcome the evils of a poor design. A good design in many cases required no fitting; and where it was possible, it was better to manage with no fitting; for the finest fitting might be undone by a little warp in the material or by a piece of grit. .... He would test the instrument by shaking it roughly, and it would be seen that there was no error in the marking."

This, it seems to me, may be called Kelvin's Second Law of Oceanographic Instrumentation: The instrument should not be dependent on lapped bearings or other precision parts for its operation.

## REFERENCES: J.B. Hersey

BERANCK, LEO L. 1949. "Aeoustic Measurements". *Wiley, New York.*

COLE, ROBERT H. 1948. "Underwater Explosions". *Princeton Univ. Press. Princeton.*

KOENIG, WALTER and others. 1946. JASA 18 19-49.

## REFERENCES; H. Nash

HOLT, LEE E. "The German Use of Sonic Listening". *JASA 19,4, 678-681 July 1947.*

URICK, R.J. "Some Directional Properties of Deep-water Ambient Noise". *NRL report 3796, Jan,16, 1951.*

## REFERENCES: Frank D. Snodgrass

Admiralty Research Laboratory. "The Generation and Propagation of Ocean Waves and Swell", *Teddington, Middlesex, England;* Feb. 27, 1947.

BARBER, N.F. and URSELL, F. "The Generation and Propagation of Ocean Waves and Swell", *Cambridge University Press, London England;* Feb. 1948

BEACH EROSION BOARD. "An Ocean Wave Measuring Instrument", *Tech. Memo. No. 6, Corps of Engineers;* Oct. 1948.

BEACH EROSION BOARD. "The Rayleigh Disk as a Wave Direction Indicator", *Tech. Memo. No. 18, Corps of Engineers;* July 1950.

BUREAU OF SHIPS. "Interim Report, 1948: Sonic Radio-Link Wave Height Meter", *U.S.Navy Radio and Sound Lab.*, Problem U24CD.

CHINN, ALLEN J. "Summary Report on Shore Wave Recorder Mark III", *Tech. Report HE-116-303, Univ. of California, Institute of Engineering Research, Berkeley;* June 21, 1949.

FOLSOM, R.G. "Wave Measurements in Deep Water with Recording Instruments", *Tech. Report HE-116 90, Univ. of Calif., IER, Berkeley;* Feb. 1, 1945.

FOLSOM, R.G. "Field Test of Shore Wave Recorders, Half Moon Bay", *Tech. Report HE-116-282, Univ. of Calif., IER, Berkeley;* Jan 15, 1946.

FOLSOM, R.G. "Sub-surface Pressures Due to Oscillatory Waves", *Trans. of Amer. Geo. Union, vol. 28, no. 5; Oct. 1947; pp. 722-724.*

FOLSOM, R.G. "Measurement of Ocean Waves", *Trans. of Amer. Geo. Union, vol. 30, no. 5;* Oct. 1949.

FUCHS, R.A. "Prediction of Linear Effects from Instrumentation Records of Wave Motion", *Tech. Report HE-116-337, Univ. of Calif., IER;* June 1952.

ISAACS, J.D. and CHINN, A.J. "Preliminary Report on the Mark II Wave Direction Recorder and Indicator", *Tech. Report HE-116-290, Univ. of Calif., IER;* June 1948.

ISAACS, J.D. and WIEGEL, R.L. "The Thermopile Wave Meter", *Trans. of Amer. Geo. Union, vol. 31, no. 5;* Oct. 1950.

KAMMER, E.W. and DINGER, J.E. "Hurrican Swell as a Generator of Microseisms", *J. of Meteorology, 8; 347-353;* October 1951.

FUCHS, R.A. "On the Theory of Short-Crested Oscillatory Waves", *Tech. Report, HE-116-326, Univ. of Calif., IER;* June 1951.

KLEBBA, A.A. "A Summary of Shore Recording Wavemeters", *Woods Hole Oceanographic Institution;* Aug. 3, 1945.

KNAPP, R.T. "Determination of Wave, Surge and Ship Motion - U.S.Naval Station, Long Beach, California", *Final Report of Contract NOy-13116, Bureau of Yards and Docks, U.S. Navy;* May 1951.

MORISON, J.R. "Analysis of Sub-surface Pressure Records in Constant Depths and on Sloping Beaches", *Tech. Report HE-116 336, Univ. of Calif. IER;* May 1952.

REFERENCES: Frank D. Snodgrass Cont'd

**MUNK, W.H.** "Tracking Storms by Forerunners of Swell", *J. of Meteorology, vol. 4, no. 2; April 1947; pp. 45-57.*

**MUNK, W.H.** "Increase in the Period of Waves Travelling over Large Distances; with Applications to Tsunamis, Swell and Seismic Surface Waves", *Trans. of Amer. Geo. Union, vol. 28, no. 2; April 1947; pp. 198/217.*

**MUNK, W.H., IGLESIAS, H.V. and FOLSOM, T.R.** "An Instrument for Recording Ultra-low Frequency Ocean Waves", *Reviews of Scientific Instruments, vol. 19, no. 10; Oct. 1948; pp. 654 658.*

**MUNK, W.H.** "Surf Beats", *Trans. of Amer. Geo. Union, vol. 30, no. 6; December 1949; pp. 849-854.*

**MUNK, W.H.** "Origin and Generation of Ocean Waves", *Proc. of First Conf. on Coastal Engineering, Council on Wave Research;* Oct. 1951.

**PUTZ, R.R.** "Wave Height Variability; Prediction of Distribution Function", *Tech. Report HE-116-318, Univ. of Calif. IER;* Dec. 1950.

**PUTZ, R.R.** "Wave Period Variability; Prediction of Distribution Function", *Tech. Report HE-116-325, Univ. of Calif., IER;* June 1951.

**PUTZ, R.R.** "Idealized Reconstruction of Ocean Surface from Measurement on Twenty-five Sub-surface Pressure Records", *Tech. Report HE-116-317, Univ. of Calif., IER;* Sept. 1950.

**RAUCH, S.E. and FOLSOM, R.G.** "Evaluation of K for the Suspended Underwater Pressure Recorder", *Tech. Report HE-116-156, Univ. of Calif., IER;* Aug. 6, 1945.

**RAUCH, S.E.** "Pressure Response at a Given Depth Below Surface", *Tech. Report HE-116-191, Univ. of Calif., IER;* Nov. 1945.

**RUDNICK, P.** "A System for Recording and Analyzing Randon Processes", *Univ. of Calif. Marine Physical Lab., San Diego;* Oct. 5, 1949.

**SCRIPPS INSTITUTION OF OCEANOGRAPHY.** *Quarterly Progress Report No. 4, Beach Erosion Board Contract W-49-055-eng-3;* April, May, June, 1950.

**SNODGRASS, F.E. and STILING, D.E.** "Operation Manual for Mark IX Shore Wave Recording System", *Tech. Report HE-116-320, Univ. of Calif., IER;* Mar. 1951.

**SNODGRASS, F.E.** "Mark VI Shore Wave Recorder", *Tech. Report HE-116-319, Univ. of Calif. IER;* May 1952.

**SEIWELL, H.R.** "Sea Surface Roughness Measurements in Theory and Practice", *Annals of the N.Y. Academy of Science, vol. 51, art. 3;* May 13, 1949.

**SEIWELL, H.R. and WADSWORTH, G.P.** "A New Development in Ocean Wave Research", *Science, vol. 109, no. 2829;* Mar. 18, 1949.

**WIEGEL, R.L.** "Tables of the Functions of d/L and $d/L_0$", *Tech. Report HE-116-265, Univ. of Calif., IER;* Jan. 30, 1947.

**WOODS HOLE OCEANOGRAPHIC INSTITUTION.** "A Bermuda Recording Installation", *Contract NObs-2083;* Aug. 1947.

## REFERENCES: W.H. Munk

**MONTGOMERY, R.B.** "The Present Position of the Study of Exchange across the Ocean-Atmosphere Interface; *pp. 131-140.* "International Symposium on Atmospheric Turbulence in the Boundary Layer". *Mass. Inst. of Techn.* June 1951.

# CHEMICAL MEASUREMENTS*

Dayton E. Carritt

## INTRODUCTION

Chemistry has contributed much to the development of the science of oceanography. Analytical chemistry has contributed the tools and techniques for detecting and measuring the dissolved and suspended constituents in the sea, thereby providing the chemical, physical, biological, and geological branches of the science with a great deal of the raw data that forms the framework of our description of the oceans. The following will be a discussion of the instruments used to carry out the chemical analyses needed in oceanography. Some of the instruments have been designed specifically for oceanographic studies. Others have been developed for use in other fields but appear, at least in principle, to be well suited to oceanographic studies.

The instrumentation of chemical operations in oceanography presents three problems. The first is concerned with shipboard operation, the second with work ashore, and the third, representing a trend in oceanography that has only recently been developed to any great extent, that of making in situ measurements with instruments that are either lowered from a ship or are attached to unattended recording or telemetering devices.

Since both shipboard and in situ recording or telemetering operations place some serious limitations on chemical procedures and instruments, it may be well to note these limitations here and to refer to them later in evaluating existing and proposed apparatus. Contrasted with a normal shore-based laboratory, a seagoing laboratory (recording or telemetering buoys fall into the latter class) has the following distinctive features:

(a) Non uniform motion along all axes in space with the associated accelerations, predominantly those from ship's roll. These vibrations have a spectrum of periods ranging from less than one second to more than fifteen seconds, and amplitudes of from fractions of a millimeter to many feet. Instruments containing moving parts which respond to these ambient accelerations obviously have limited application. For example, a high sensitivity meter containing the usual moving coil galvanometer is generally useless. However, Leeds and Northrup does produce a high sensitivity Marine Galvanometer of this type (L. and N. No. 2255). Ship's motion also limits the number and kind of operations that an analyst can efficiently perform. The simultaneous adjustment of two devices is often difficult, whereas, given free hand to serve as an anchor, an analyst can often make a single adjustment satisfactorily.

---

* - Contribution No. 10 from the Chesapeake Bay Institute of The Johns Hopkins University.

(b) Electrical power on most ships has regulation of voltage, frequency, and wave form that is inferior to the regulation of most commercial power. The efficiency of instruments requiring well regulated supplies is thus often reduced on shipboard unless supported by costly secondary supplies or regulators. Battery-operated instruments obviously overcome a part of this difficulty, and except when working immediately offshore have to be used in recording or telemetering equipment.

"Sea water batteries", in which sea water is the electrolyte and a relatively reactive metal such as magnesium serves as one of the electrodes, conceivably could find application in situations where the battery or the entire instrument is to be jettisoned.

(c) Maintenance and repair facilities are much more limited at sea than ashore.

The efficiency of a seagoing instrument for chemical measurements, then, can be judged by the following criteria: (1) it should be unaffected by motion and vibration; (2) it should be simple to operate (especially if put in the hands of semi-skilled technicians); (3) it should be able to operate efficiently with poorly regulated power supplies or with batteries; and (4) it should require a minimum of maintenance while at sea.

## CHLORINITY-SALINITY-DENSITY MEASUREMENTS

One of the persistent problems in chemical oceanography is that of devising a simple, rapid, accurate, and precise method for the determination of sea water density. A great deal of work has been done to avoid the direct determination of density which is considered too time-consuming and delicate for routine operations. It should be noted, however, that modern, direct-reading analytical balances, precision thermostats, and plastic sample bottles make the direct determination now much more feasible than in the past.

The classical works of Dittmar and his contemporaries on the composition of sea water were expanded by Knudsen and Patterson to establish a standardized, indirect density measurement now known as the Knudsen Method (Oxner, 1946). This method uses a relatively simple titrimetric procedure which gives results that can be directly converted to density with the aid of Knudsen's Hydrographical Tables. Despite the simplicity of the Knudsen Method, which can be carried out on shipboard as well as ashore, it has undesirable features when a large number of samples must be processed. The undesirable features appear to be associated with human error rather than with any inherent technical inconsistency in the method. Under controlled conditions with competent technicians, the titration will give salinity values with an error not over ± 0.02 $^{o}/oo$.

To maintain this accuracy when several technicians are involved apparently is difficult. It is possible to obtain a measure of the accuracy and precision of the results from each of several operators by interspersing samples of known or standard solutions with field samples in such a way that the operators have no way of distinguishing between the two. The results of two such tests, the only ones known to the author, have not been published. They did indicate, however, that improvement was needed in order that the resulting density values be useful in computations in physical oceanography. Continued checks of this sort are time-consuming and by themselves give no indication of the real source of errors, except of course to point out grossly incompetent technicians.

Frequently, it is difficult to persuade competent technicians to remain on such routine jobs. Continual education of new men must therefore take place, and a good personnel office and training program are necessary adjuncts to the chemistry group.

Attempts have been made to devise methods which eliminate some of the undesirable features of the Knudsen titration. The measurements of the nearly colligative properties of sea water, the application of electrometric methods for the determination of the equivalence point in titrimetric procedures, and more recently the application of high frequency techniques employing cells with no internal electrodes have been tried.

The measurement of electrical conductance has considerable appeal because of the relative ease with which an in situ continuous recording instrument can be adapted to the determination. The extensive publications of Jones and his co-workers, Shedlovsky, and Parker and Parker provide adequate guides to the instrumentation of the method. Thomas, Thompson and Utterback (1934) have determined interpolation formulas for specific conductance as a function of chlorinity at five degree intervals in the temperature range 0° to 25°C. Pollak (unpublished results) has found certain minor inconsistencies in the Thomas, Thompson and Utterback formulas which in part may be accounted for by a geographical factor in the conductivity-chlorinity relationship or possibly because some of their samples had been stored in glass containers. Wenner, Smith and Soule (1930) describe a seagoing conductivity instrument which, if judged solely on accuracy and precision, provides data comparable with that from the Knudsen titration. The instrument was used on the last cruise of the CARNEGIE and on several of the United States Coast Guard ice patrol vessels. Its main disadvantage appears to be in the length of time required to attain temperature equilibrium before the conductivity measurements can be made. Samples must remain in the thermostated cells for 15 minutes, and even with the multiple-celled instruments 30 to 50 measurements per day is the best that can be expected.

Sea water slowly dissolves glass containers with a resulting increase in total dissolved solids and conductivity but little or no change in halide content. Samples for conductimetric analysis, then, should be stored in glass for only relatively short periods. Plastic bottles, available from most chemical supply houses, appear to be well suited for the storage of sea water samples. They not only are unreactive with sea water but are nearly unbreakable, and if not completely filled, will withstand freezing.

Despite the several shortcomings, the conductance method and particularly the Wenner instrument is considered by many to be superior to other methods for routine chlorinity analyses.

The salinity-temperature, depth recorder (STD), developed by the Woods Hole Oceanographic Institution and described by Jacobson (1948), provides a continuous trace of those variables on a three channel strip chart recorder. An underwater unit composed of a conductivity cell, a nickel resistance thermometer, and a pressure operated depth element is connected by a multiconductor cable to the deckside unit which contains the amplifiers, salinity computing circuit, and the recorder. The recorder provides traces of salinity in two overlapping ranges, 20 °/00 to 32 °/oo and 28 °/oo to 40 °/oo, temperature in the range 28° to 90°F, and depth in two ranges up to 1200 feet. The lower limit of 20 °/oo in the salinity range restricts the usefulness of the instrument in nearshore operations and the design error of 0.3 °/oo in salinity limits its utility in open ocean studies. Nevertheless, it has been used with considerable success in studies in which extreme range and high precision are not needed. The auth-

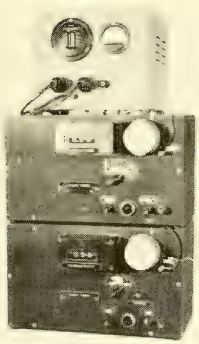


Fig. 1. Conductivity Temperature Indicator (CTI). A. Deck-side units. Top unit contains constant voltage transformer, and meters for monitoring voltage and frequency of supply to instruments. Center unit, temperature indicator. Bottom unit, Conductivity indicator. Dials read temperature in degrees centrigrade and conductivity in millimhos, respectively. Circular unit to right of dials contain indicating dehydrating agent. Middle, four position switch on each unit has three calibrate positions and a "normal use" position. Bottom row of controlls are, right to left, fuse, powre switch, power indicator light, and switch to turn the balancing motor on and off while keeping unit energized.

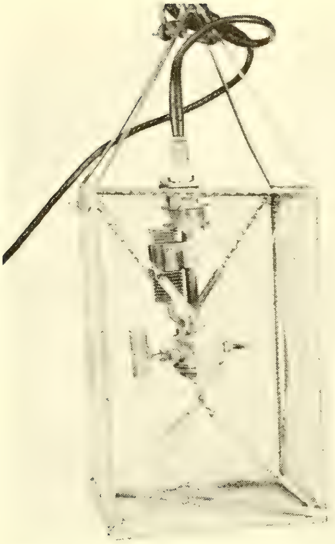


Fig. 1. B. Underwater head. Sensing elements and junction box suspended on eight springs. Portion protruding through top of cage is water proof connector for MCOS-6 cable. Entire unit below water proof connector is oil filled, bellows on left prevent pressure differential across case. Conductivity cell on right, resistance thermometer on leucite web on left.

or knows of no instrument other than the STD and the CTI, the latter to be described below, which exist in anything but pilot models.

The Navy Electronics Laboratory at San Diego, California, is reported to be building a salinity-temperature-depth recorder which uses a thermistor for the thermal unit, and a conductivity cell of the same design as that used in the CTI. There is no information available concerning the operating characteristics of this instrument.

A conductivity-temperature indicator (CTI) has been constructed by the Chesapeake Bay Institute of The Johns Hopkins University. The instrument was designed primarily for estuarine studies and so has a conductivity range to cover salinity from 0 $^{o}$/oo to 35 $^{o}$/oo and a temperature range of -2$^{o}$ to 32$^{o}$C. The instrument contains no depth measuring element. In relatively shallow estuarine waters depth can be estimated adequately by measuring the length and angle of the lowering cable. The underwater element consists of a two electrode H-type conductivity cell* and a nickel resistance thermometer. Temperature in degrees Centigrade and conductivity in millimhos are indicated on a pair of four digit counters mounted on the amplifier and servo mechanism housing. Pictures of the instrument and a schematic drawing of the circuits are shown in Figures 1 and 2. Wherever possible, commercially available components have been used

---

* - Conductivity cell manufactured by Kahl Scientific Instrument Corp., El Cajon, California.

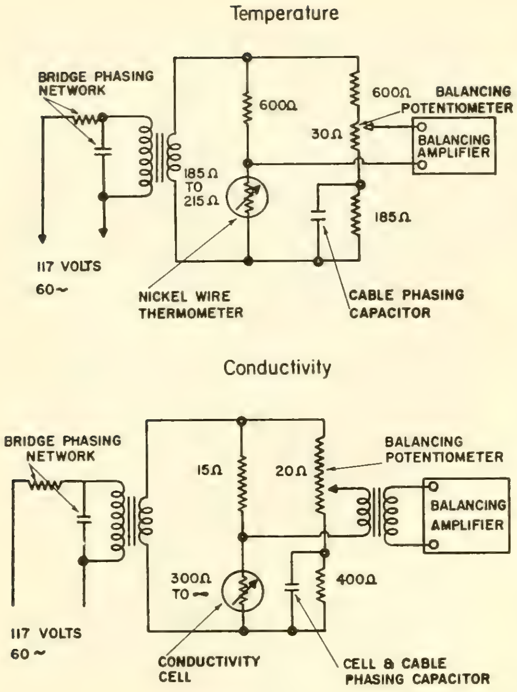

Temperature
BRIDGE PHASING NETWORK
600Ω
600Ω BALANCING POTENTIOMETER
30Ω
BALANCING AMPLIFIER
185Ω TO 215Ω
185Ω
117 VOLTS 60~
NICKEL WIRE THERMOMETER
CABLE PHASING CAPACITOR
Conductivity
BRIDGE PHASING NETWORK
15Ω
20Ω
BALANCING POTENTIOMETER
BALANCING AMPLIFIER
300Ω TO ∞
400Ω
117 VOLTS 60~
CONDUCTIVITY CELL
CELL & CABLE PHASING CAPACITOR

**Fig. 2. Schematic equivalent circuits of CTI temperature and conductivity units. Commercial components have been used where possible.**

in construction. Three CTI instruments have been constructed and have been in use for about three years. The operating characteristics of the CTI are discussed in a later section.

Von Arx (1947) described *A Salinometer for Use in Brackish Water.* The instrument is unique in that its response to variations in salinity depends upon the behavior of a pair of electrodes that have been subjected to extreme but controlled polarization when immersed in sea water. The electrodes, one of copper and the other of zinc, become coated with relatively insoluble salts of the metals during polarization, $ZnCO_3$ on the zinc and mixture of basic carbonate and hydroxide on the copper. Thus a "battery" is formed, the potential of which is controlled by electrode reactions of the type;
$Zn \rightleftarrows Zn^{++} + 2e$ and $Cu \rightleftarrows Cu^{++} + 2e$.
Since the composition and solubility of the solids formed during polarization are nearly independent of salinity over a wide range of dilution, the potential of the "battery" will be nearly constant regardless of the salinity of the water in which polarization occurred.

When used to measure salinity, the "battery" is connected across the coil of a milliammeter and with this constant external load the current through the circuit is limited by the resistance of the sea water path between the electrodes. Thus, the current drawn from the cell can be used as a measure of salinity, since variations in the latter control the internal resistance of the cell.

A plot of current vs. time for the discharge of a pair of polarized electrodes resembles the familiar discharge curve of a storage battery. The current is initially high, drops rapidly to a plateau, and then falls rapidly again. The magnitude of current in the plateau region has been shown to be an exponential function of salinity. Unfortunately, the duration of the current plateau is short, one to two minutes depending on the salinity. It becomes necessary then to repolarize the electrodes frequently during use. Irreversible changes in the electrodes may occur unless repolarization is controlled. Ideally, the electrodes should be "backed up" until the discharge current during the first part of a current reading corresponds to the lower part of the first knee of the discharge curve.

The effects of variations in temperature have been very nearly eliminated by placing a resistance in series with and mounted directly on the electrodes. The compensating resistance was constructed to have a temperature coefficient of equal magnitude but of opposite sign to that of the electrical resistance of sea water. It seems reasonable to assume that the current plateau in the discharge curve might be extended in time by providing a means of mechanically entrapping polarization products at the surface of the electrodes.

The instrument is extremely portable and well suited to use in small boats or as a pack load. A single case contains all of the meters, switches, and batteries as well as storage space for the electrodes and cable. A calibration curve shows its most useful range to be from 0 $^{o}/oo$ to 20 $^{o}/oo$ salinity in which range the probable error in salinity is approximately ± 0.2 $^{o}/oo$.

Parrack and Jensen, referred to in a Texas A. and M. progress report (1952), give a brief description of a recording salinity meter which uses a conductivity cell as the sensing element.

> "The electrode system consists of four monel rings fixed in a glass tube within the water line. A regulated A.C. voltage is impressed across a resistance in series with the two outer electrodes such that the impressed voltage is divided between this series resistor and the resistance of the water column. This division is controlled by the conductance of the water column between these outer electrodes. The two inner electrodes measure the IR drop across the water column between them by use of a vacuum tube voltmeter. The variation in signal is eventually read as a current on an Esterline-Angus Recording Milliammeter. It is not feasible to cover the entire salinity variation in a single range, consequently four range resistors are used so as to divide the variation over four ranges".

The accuracy and long range stability of the instrument is not known, as a full report has not yet been published. The electrode arrangement, similar to that described by Shedlovsky (1930), achieves partial separation of the system applying a potential to the cell from the system measuring the IR drop. The stability of monel electrodes is questionable for copper is known to slowly dissolve from monel in sea water.

More important than details of the construction of these *in situ* instruments is the consideration of the fundamental design principles. Each of the instruments mentioned gains its primary information from the electrical resistance between a pair of electrodes placed in the water. The measurements with these instruments can only be as reliable as the ability of the electrodes and indicating devices to measure the true resistance of the solution between them.

In a sense, many of the problems encountered in the design and use of *in situ* conductivity instruments are similar to those met in the studies that gave the absolute values of the conductance of reference solutions such as potassium chloride that are now used as standards for the calibration of conductivity cells.

Jones and his co-workers (1931, 1933), Parker and Parker (1924), and Shedlovsky (1930) give detailed descriptions of the fundamentals of conductimetric measurements. In all high precision studies, much emphasis is placed on the treatment of the conductivity cell not only during platinization but also during the cleaning, washing, and drying of smooth platinum electrodes prior to making the conductivity measurements. For example, Morgan and Lammert (1923) note that the apparent resistance of a cell having smooth platinum electrodes varied by two to three per cent depending on the method used for cleaning the cell. They attribute at least a part of the variation to the formation of a galvanic cell composed of the cell electrodes and plated or absorbed contaminations. In any event, the use of a conductivity cell over long periods without calibration brings up many stability problems not evident when such a cell is used with frequent calibration.

In the design of *in situ* conductance devices, many changes must be made from the cell design and electrode treatment shown to be desirable by laboratory experience to meet the need for adequate flushing of the cell, mechanical stability, and other factors connected with operation at sea. The effect of these changes on the precision and accuracy of the instrument can be only estimated, so that calibration is imperative. Calibration implies the existence of a standard with characteristics at least as good as the expected characteristics of the instrument. A generally accepted rule of thumb is that the standard should be an order of magnitude better than the test instrument.

Experience with the CTI has emphasized another requirement of calibration systems that frequently can be or has been neglected. The CTI, like all in situ conductance instruments, was made to function in an environment in which the variable to be measured fluctuates in time. This raises two difficulties in the calibration of such an instrument. First, if the time constant of the instrument is large (slow response time) compared with the fluctuations in the environment, a calibration of the instrument made under static conditions will not provide a true indication of the reliability of a measurement made in the fluctuating environment. Second, if the time constants of the standard and of the test instrument are very different, comparison of the two in a fluctuating system may not give a reliable measure of the accuracy and precision of the test instrument.

In the following discussion some of our experiences in attempting to calibrate the CTI will be presented. The behavior of this particular instrument is given because it is the most familiar to the author. However, many of the features are believed to be common to other similar instruments, especially to the STD which uses a thermometer unit similar to the CTI, and to the proposed NEL instrument which is reported to use an H-type conductivity cell.

The first calibrations of the CTI were carried out in a 55 gallon barrel. The sea water in the barrel was both cooled and diluted by the addition of ice. CTI readings, standard thermometer readings, and samples for chlorinity titration were taken after each addition of ice had melted and vigorous stirring achieved at least a steady thermal state as shown by the instruments. The CTI thermometer readings were then compared with the standard thermometer values for each set of observations, thus providing a calibration of the CTI thermometer in terms of the standard, National Bureau of Standards certified mercury thermometer. Conductance values were calculated from standard thermometer temperatures and chlorinity titration results, using the Thomas, Thompson and Utterback (1934) interpolation formulas. These computed values were then compared with similar values obtained from CTI temperature readings, CTI conductance readings, and a previously measured cell constant. Thus, the behavior of the CTI was compared with a standard composed of a National Bureau of Standards certified thermometer and the chlorinity titration. This technique was noted at the time to be crude, as thermal equilibrium in the container was difficult to maintain, especially when the ambient temperature was several degrees from the test temperature. It was under these conditions that the difference in time constants between the mercury standard and CTI resistance thermometers was noted.

"Barrel" calibrations of this sort provided a means of setting the range adjustments and making circuit refinements in the instrument. They are inadequate, however, for precise calibrations when standard deviation of the order of hundredths of degrees centigrade and hundredths of parts per thousand chlorinity are to be noted. These calibrations did, nevertheless, indicate that the CTI resistance thermometer was a stable instrument. Successive thermometer calibrations made several months apart gave essentially the same mean curve but since the temperature of the water in the barrel was not sufficiently homogeneous, the observed deviations from the mean could not be attributed entirely to the CTI. On the basis of these calibrations the CTI thermometer was judged to be a more reliable instrument than the conventional bucket type mercury thermometer commonly used for obtaining surface temperatures at sea.

A second series of calibration data was obtained from field observations. The CTI underwater head was held just awash at the side of the ship and the deck-side units read at a time when the instrument indicated the water to be homogeneous. At the same time a sample of water to be used for chlorinity titration was taken immediately adjacent to the underwater head. The temperature at the sampling spot was obtained either with the CTI thermometer assuming the calibration to be adequate, as was usually done, or with a calibration "bucket-thermometer." Conductance computations were made from these data as in the case of "barrel" calibrations. Thus, a comparison of the chlorinity computed from CTI measurements with a standard consisting of the chlorinity titration was possible. In theory this method of calibration has the advantage of comparing the test instrument with the standard under the same conditions that exist during normal use of the instrument.

In calibrations of this kind an unavoidable subjective decision is often required. Ideally, the sampling done by the test instrument (the CTI) and the standard (the chlorinity sample collecting bottle) should be in a homogeneous body of water. Unfortunately, this frequently is not the case as it is not uncommon to observe small, rapid changes in the conductivity reading and small slower changes in the temperature reading of the CTI. The observer, therefore, is frequently required to decide when the fluctuations are sufficiently small to be neglected.

The observation that the time constant of the conductivity unit is smaller than that of the thermal unit leads to an important property of the instrument. If these constants were equal, the combined input signals when converted to chlorinity would be distorted (the peaks of the fluctuation reduced). With unequal constants there will be both distortion and phase shift. It is thus an open question whether the chlorinity values from CTI data and from chlorinity titrations are sufficiently comparable. They probably are, but as yet there is no completely objective way of answering the question.

A set of calibration figures is presented in figure 3, in which the CTI conductivity scale readings has been plotted against conductivity computed from chlorinity titration and CTI temperature data using the interpolation formulas of Thomas, Thompson and Utterback (1934). It has been estimated that a $2\sigma$ band around the mean would be of the order of 0.5 millimho (approximately 0.5 Cl$^{o}$/oo). This amounts to about ten times the variation expected from design considerations had the standard been absolute.

Thus, neither the barrel nor field calibrations as so far discussed provide data from which a satisfactory picture of the behavior of the instrument can be found.

Since these data were taken, investigations of three aspects of the calibration problem have been initiated. They are: (1) static calibration, (2) characteristics of the H-type conductivity cell, and (3) precision estimates from paired measures.

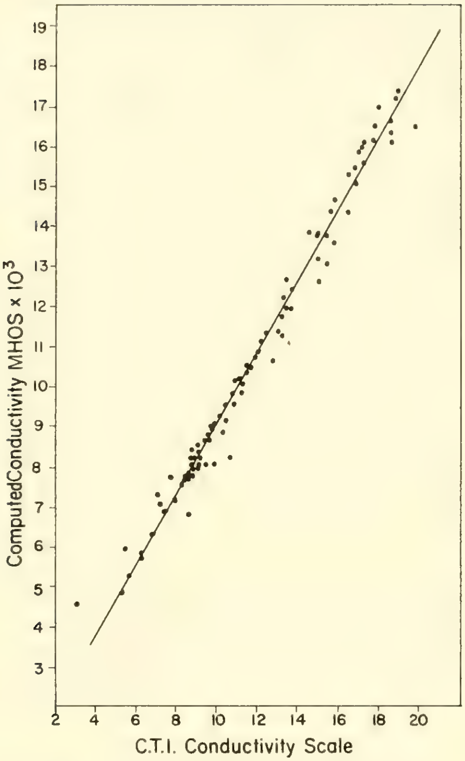


**Fig. 3.** CTI field calibration. Computed conductivity obtained by using titration chlorinity results, CTI temperature, in the Thomas, Thompson, and Utterback interpolation formulas. Data obtained over several months period during winter of 1951-52.

(1) A calibration tank having provision for temperature control and rapid circulation of the water has been constructed. In it, approximately 120 gallons of water come in contact only with rubber or plastic (except for three lead-sheathed heaters)and is circulated by a 40 gallon per minute plastic pump. Plastic coated refrigeration coils provide means of operating below room temperature. When this tank can be placed in operation, it should provide the means of presenting a homogeneous environment to test instrument and standards, thus furnishing a measure of the reliability of the instrument under static conditions.

(2) Three characteristics of the H-type conductivity cell were measured in the laboratory where considerably more control over environmental conditions and measuring circuits is possible than with the complete CTI. The characteristics measured were frequency and temperature coefficients, and cell stability.

The H-type conductivity cell was set up in a thermostated plastic container. The energizing and measuring circuit was a conventional alternating current bridge composed of a variable frequency oscillator, balancing resistors and capacitors, and a vacuum tube voltmeter. Provision was made to measure the stability of the circuit itself by the substitution of a fixed RC network in place of the conductivity cell. With this arrangement the effects on the apparent conductance of the H-type conductivity cell produced by various methods of cleaning the cell, by changes in frequency in the range 70 cps to 3000 cps, and by changes in temperature in the range 16° to 32°C were measured. The results of some of these measurements are summarized below.

The conductance of the cell was measured at 70, 150, 400, 1000 and 3000 cps, at five temperatures as the cell and solution were warmed from 16° to 32° C and at the same temperatures while cooling through the same temperature range. The measurements were made over a period of approximately five hours. The results are shown in figure 4. It will be seen that the effect of variations in frequency at any one temperature are rather large. In the interval 70 to 150 cps, an apparent change of 0.01 millimho (approximately 0.01 Cl °/oo) would be produced by a frequency change of 0.8 cp. Transient frequency changes of about 1.0 cps are not uncommon with generators normally used on shipboard. The results of these measurements prompted the inclusion of a frequency meter in the control box now used with the CTI (the topmost box in the stack shown in Figure 1A). Nevertheless, the effect of changes in frequency by itself apparently cannot account for the approximately 0.05 Cl °/oo spread meas-

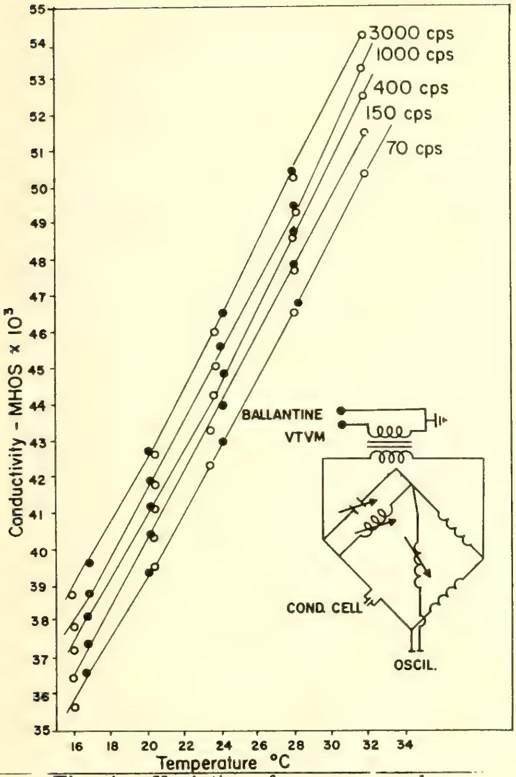


Fig. 4. Variation of apparent conductivity cell as a function of frequency and temperature. Insert is schematic of circuit containing conductivity cell. Sequence of measurements was 16°C, 70 to 3000 cps; 20°C, 70 to 3000 cps; etc. to 32°C, and then repeat as system cooled to 16°C. Open circles measurement on heating cycle; closed circles while cooling.

ured in field calibrations. This change would require frequency to drift by 40 cps.

In addition to giving a measure of the frequency coefficient of the H-cell, the measurements shown in figure 4 indicate what appears to be either a long term drift in the apparent conductance of the cell or a hysteresis produced by heating and cooling. The two measurements at 16°C, taken approximately five hours apart, show a small increase in apparent conductance. The magnitude and direction of the long term drift noted above was observed over a period of three days by measuring the apparent conductance of the cell at frequent intervals at 70 and 1000 cps. Except during the 70 cps measurements, the bridge was energized at 1000 cps. During a three hour period the apparent conductance was seen to decrease, pass through a minimum, and then slowly increase. During the three days a spread of nearly 0.3 millimho was observed. At the end of the three days' immersion the cell was covered by what appeared to be a bacterial slime. (The test solution was filtered sea water.) Removal of the slime by passing a pipe cleaner through the cell increased the apparent conductance by 0.6 millimho. Careful cleaning with nitric acid followed by thorough rinsing in distilled water increased the apparent conductance an added 1.06 millimhos. After cleaning, measurements showed a slow decrease for 17 hours at which time the apparent conductance was 0.3 millimho below its original value. The changes in millimhos are nearly equivalent to changes in chlorinity units.

The temperature coefficient estimated from these data is similar to that predicted from the Thomas *et al.* (1934) measurements, i.e., $0.01\,^{\circ}\mathrm{C} \cong 0.01$ Cl $^{\circ}/\mathrm{oo}$.

The results of these measurements are given not for their quantitative aspects but rather to show that the condition of a set of electrodes will have a marked influence on the measured conductivity. The results suggest that for precision *in situ* measurements some standardized method of cleaning and aging the electrodes may be desirable.

(3) An estimate of precision obtained by a statistical analysis of simultaneous measures from two CTI instruments was made by Mr. Blair Kinsman, Instructor of Oceanography at the Chesapeake Bay Institute. He reports as follows:

"Pending completion of a calibration tank, it was felt that an estimate of the precision of the CTI could be secured from field data analyzed according to the method given by Grubbs (1948). During a cruise when fairly homogeneous conditions were to be expected, the heads of instruments No. 2 and No. 3 were lowered together and 678 and 679 pairs of simultaneous measurements of temperature and conductivity, respectively, were made. The means of the measures (see Table I) were taken as indicating a systematic difference of 0.02 in the instruments in both temperature and conductivity. The data were corrected by subtracting 0.01 from each reading from CTI No. 2 and adding 0.01 to each reading from CTI No. 3. Analysis by the Grubbs method for partitioning the variance into that attributable to the environmental variation and that due to instrument variation gave the estimates shown in Table I $\sigma_x^2$ is an estimate of the variance of the environment had there been no instrument errors. $\sigma_{e\#2}^2$ and $\sigma_{e\#3}^2$ are estimates of the variances of the random errors inherent in the instruments".

TABLE I

| Measure | Instrument | Number of measures | Mean of corrected measures | est $(\sigma_x^2)$ | est $(\sigma_e^2)$ |
|---|---|---|---|---|---|
| Temperature | CTI No. 2 | 678 | 7.24 | 0.045270 | 0.000800 |
| | CTI No. 3 | | 7.22 | | 0.000370 |
| Conductivity | CTI No. 2 | 679 | 9.48 | 6.598635 | 0.012676 |
| | CTI No. 3 | | 9.46 | | 0.025607 |

"Grubbs (1948) says: 'It is to be noted that the variance of the estimate, est. $(\sigma_1^2)$ depends on (a) $\sigma_x^2$, the variance in the characteristic measured, (b) $\sigma_{e1}^2$, the variance of the errors of measurement of instrument $I_1$, (c) $\sigma_{e2}^2$, the variance of the errors of measurement of instrument $I_2$, and (d) $\sigma$ n, the number of observations in the sample. It is seen, therefore, that in order to obtain a precise estimate of $\sigma_{e1}^2$ when using only two instruments, the variation in the characteristic measured, i.e., $\sigma_x^2$, should be held to a reasonable minimum or the sample size, n, should be sufficiently large.' He also says: 'The efficiency with which the absolute values $x_1$, $x_2$, ......$x_n$ are measured depends on (1) the relative size of $S_e^2$ and $S_x^2$ ....' So far we have been able to determine, the correct method of comparing $S_e^2$ and $S_x^2$, i.e., est. $(\sigma_e^2)$ and est. $(\sigma_x^2)$, is not known.

"It would seem, however, that $\sigma_x^2$ for the temperature is sufficiently small and n is sufficiently large so that est. $(\sigma_{e2}^2)$ and est. $(\sigma_{e3}^2)$ should be good estimates for the temperature errors. Unfortunately, the conductivity measures do not exhibit a comparable homogeneity. Still, the orders of magnitude of est. $(\sigma_x^2)$ and est. $(\sigma_e^2)$ for the conductivity are relatively the same as those for temperature. It would seem, then, that had the fluctuations in the environment for conductivity been as restricted as those for temperature the estimates of precision for conductivity would have been of the same order as those obtained for temperature.

"From this analysis we estimate the standard deviation of the errors of measurement for the CTI as not greater than 0.05°C and 0.05 Cl °/oo."

There appears to be common agreement among all who have used conductimetric methods for in situ salinity measurements that many problems connected with cell design and electrode behavior must be solved before an instrument having the reliability and precision of the Knudsen method can be constructed.

The use of high frequency techniques permits the measurement of the dielectric properties of a solution in a cell in which the solution does not come in contact with the electrodes. The measurements can be interpreted in terms of the concentration of substances in solution. Jensen and Parrack (1946) described an instrument and procedures for a variety of titrations. A Survey of High Frequency Oscillators and Their Chemical Application by Flom and Elving (1950) describes the state of the art up to October 1950. A brief description of the commercially available Sargent Model V Chemical Oscillometer is given by Muller (1952).

The application of high frequency techniques to the direct determination of chlorinity appears to be limited by the lack of sensitivity of relatively low frequency oscillators and the lack of stability of high frequency oscillators. The Texas A. and M. Research Foundation, with sponsorship from the Bureau of Ships, is making an Investigation of High Frequency Oscillometric and Bridge Methods of Measuring Conductivity of Solutions.

When stable oscillators can be constructed of high enough frequency to permit measurements with the desired precision, it would appear that many of the troubles encountered with electrodes in the older type of conductance measurement will be overcome.

Some of the subjectiveness of the Knudsen titration lies in the visual determination of the chromate end point. The substitution of a potentiometric determination for the visual would, in principle at least, improve the situation. Potentiometric titrations are common in analytical chemistry. The potentiometric titration of halides with silver nitrate using a silver, silver halide indicator electrode is described in many quantitative analysis texts and references. It is natural, then, to attempt to adapt these methods to improve the Knudsen titration.

Lingane (1948) described an automatic potentiometric titration apparatus in which the potential of a silver, silver halide electrode vs. a saturated calomel electrode was made to control the flow of a silver nitrate solution during the titration of a chloride or iodide solution, and to stop the delivery of the titrant at the equivalence point. As the result of the analysis of several chloride solutions, he concluded, "It is evident that the automatic titrations are fully equal in both precision and accuracy to the manual methods of titrating chloride ion with silver ion."

Carritt, Rakestraw, Snodgrass and Isaacs incorporated these principles in the design of an automatic titrator made especially for the chlorinity titration. The instrument was called the Automatic Chlorinity Titrator (ACT-I). The construction and testing of the instrument has been carried on recently by Folsom, Snodgrass and Isaacs at the Scripps Institution of Oceanography.

Prototypes of the instrument have been in routine operation at the Scripps Institution of Oceanography for the past three years. Changes in design have been made to eliminate undesirable features that appeared after continued use. Modifications of the basic instrument are recorded in Scripps Institution of Oceanography. Pictures and a block diagram of the instrument are shown in figures 5 and 6.

The heart of the ACT-I lies in the electrode reactions and their associated potentials. If a piece of silver wire coated with silver chloride is in contact with a solution in which chloride ions are being precipitated as silver chloride,

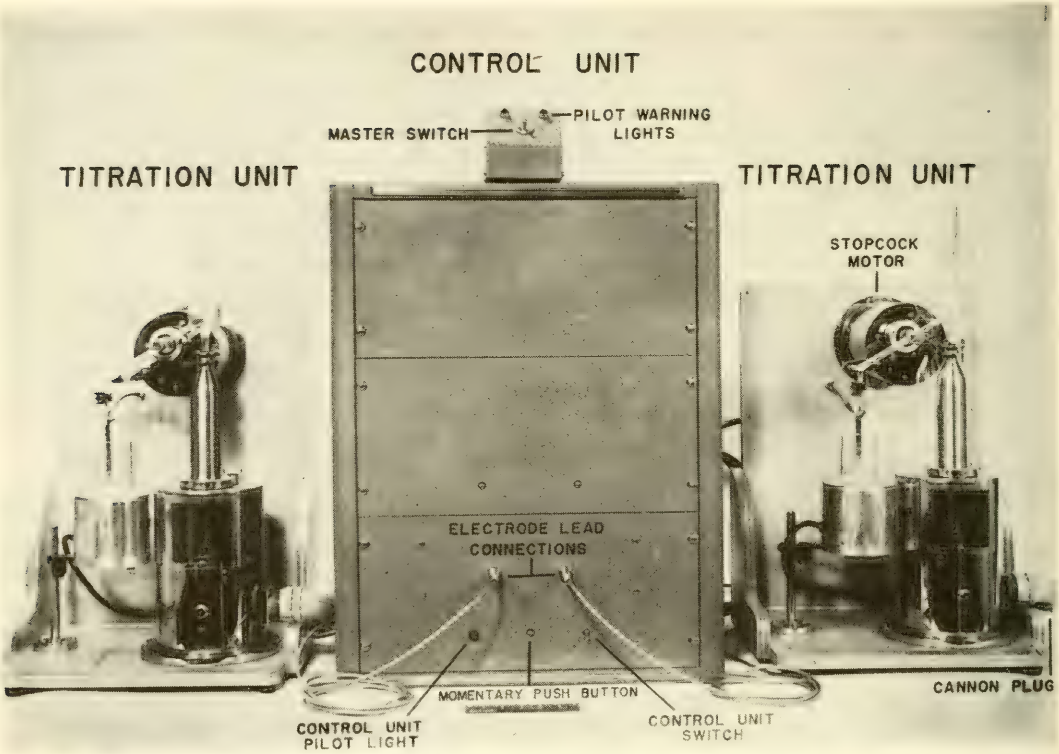

CONTROL UNIT
MASTER SWITCH
PILOT WARNING LIGHTS
TITRATION UNIT
TITRATION UNIT
STOPCOCK MOTOR
ELECTRODE LEAD CONNECTIONS
MOMENTARY PUSH BUTTON
CONTROL UNIT PILOT LIGHT
CONTROL UNIT SWITCH
CANNON PLUG

Fig. 5. **The Automatic Chlorinity Titrator (ACT-I)**

the potential of the electrode, measured against a suitable reference, will be predictable at all stages of titration and will be related to the volume of silver nitrate added as shown in figure 7. These data were obtained during a manual titration of a sample of sea water by measuring the potential of the cell Ag: $AgCl(s)\ Cl^{-}(aq)$ :: $Ag^{+}$ :Ag after the addition of each increment of silver nitrate solution. Figure 8 is a plot of $\Delta$ emf/$\Delta$ Cl$^{o}$/oo against the mean chlorinity calculated from the titration curve data. Volume of silver nitrate has been converted to chlorinity units in this curve. The magnitude of the "derivative" in the region of the equivalence point gives an indication of the precision that can be expected in the chlorinity measurement for a given difference between the equivalence point potential and any measured potential. For example, the maximum slope is approximately 800 mv per chlorinity unit. Thus an error of ±1 mv in potential amounts to only ±0.00125 Cl $^{o}$/oo, or, in order to obtain the precision demanded of the Knudsen method, ±0.01 Cl $^{o}$/oo, the potential measurement must be good to ±8 mv.

Theoretically, the potential of the cell can be used as a measure of chloride ion concentration only when no current is drawn from the cell. Under these conditions the electrodes are operated reversibly and the potential of a silver, silver chloride electrode will be related to the concentration of chloride ions by the familiar Nernst relation. In practice, it is impossible to measure the potential of a cell without drawing current from it. It becomes necessary then to find to what extent the electrodes can be "worked" and retain the desired precision and accuracy between the emf and concentration. Theory does not provide a basis for making a reliable estimate of the extent to which "working electrodes"

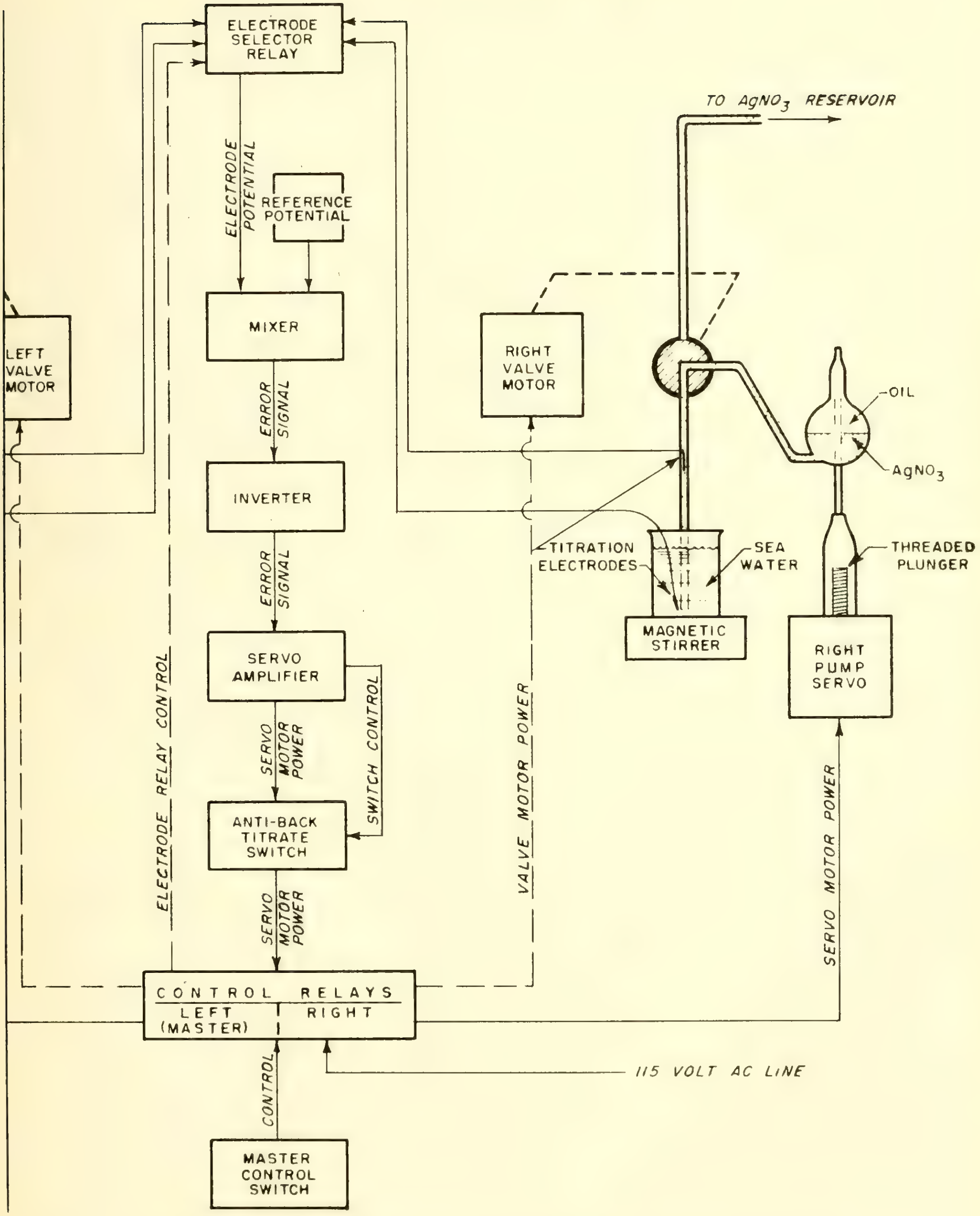

ELECTRODE SELECTOR RELAY
ELECTRODE POTENTIAL
REFERENCE POTENTIAL
MIXER
ERROR SIGNAL
INVERTER
ERROR SIGNAL
SERVO AMPLIFIER
SERVO MOTOR POWER
SWITCH CONTROL
ANTI-BACK TITRATE SWITCH
SERVO MOTOR POWER
ELECTRODE RELAY CONTROL
LEFT VALVE MOTOR
RIGHT VALVE MOTOR
VALVE MOTOR POWER
TO AgNO3 RESERVOIR
OIL
AgNO3
TITRATION ELECTRODES
SEA WATER
THREADED PLUNGER
MAGNETIC STIRRER
RIGHT PUMP SERVO
SERVO MOTOR POWER
CONTROL RELAYS
LEFT (MASTER)
RIGHT
115 VOLT AC LINE
CONTROL
MASTER CONTROL SWITCH

Fig. 6. Block diagram, Automatic Chlorinity Titrator, showing Servo System and Right Titration Unit.

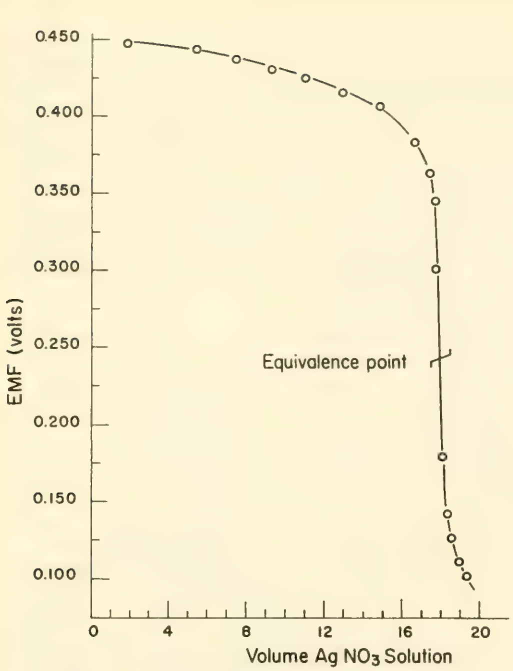


Fig. 7. Potentiometric titration curve of sea water with silver nitrate. Indicator electrode was Ag:AgCl. Reference electrode was Ag:Ag

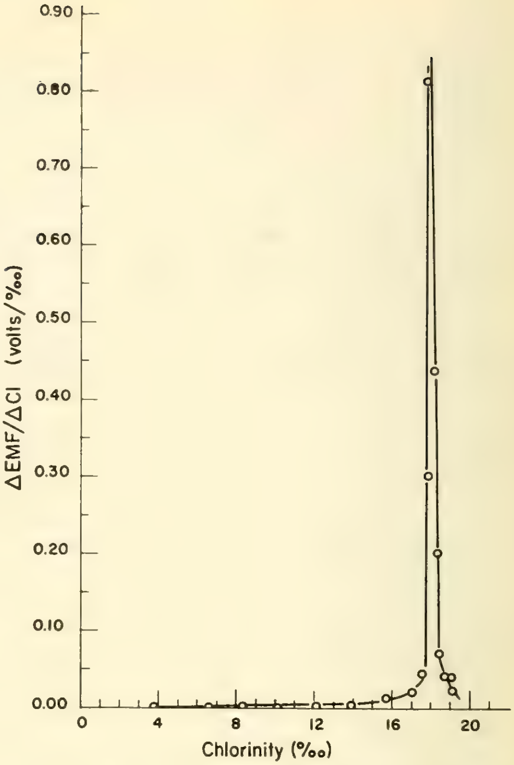


Fig. 8. Derivative curve for potentiometric titration of sea water with silver nitrate. Maximum of this curve corresponds to equivalence point shown in Figure 7.

destroy this relationship. However, the qualitative effects of variations in several factors that can be controlled experimentally are known. When current is drawn from a cell, the electrodes are polarized. The result is similar to that obtained by energizing electrodes in a conductivity cell with a D.C. signal or A.C. of poor wave form. In the case of the cell in the ACT-I, silver chloride is either made or destroyed at the indicator electrode and silver either plated out or put into solution at the reference electrode, depending on the direction of current flow. In either case the potential of the electrodes will change. Actually, drawing current from the cell is of secondary importance. The important variable is the current density at the electrodes. It is possible to reduce polarization effects by decreasing the current density. This can be achieved either by increasing the area of the electrodes or, if the sensitivity of the measuring equipment will permit, by decreasing the current drawn from the cell.

In the Lingane (1948) apparatus the circuit was arranged so that a current of 4.65 microamperes per volt would flow through the cell. Under these conditions Lingane concludes, "the current is so small that the 'electrolysis error' at the indicator electrode is negligible." Although this does not give a complete indication of polarization effects, the precision and accuracy of his titration suggest that they are small.

In the present titrator circuit the current drain on the electrodes is held to less than 0.005 microampere, and the apparent impedance of the input system is of the order of 20 megohms. A circuit having these characteristics when coupled with the electrodes presently used in the titrator effectively eliminates electrolysis errors and potential drift due to "working electrodes."

In the block diagram, figure 6, the error signal is the difference between the electrode potential and the reference potential. The latter is set equal to the end point potential of the titration. This arrangement is convenient not only from the point of view of the construction of a closed-loop servo-system, but also it is the means of reducing the current drain on the electrodes to a minimum at the end-point.

In the ACT-I, as in the Lingane apparatus, the geometric arrangement of the indicator electrode with respect to the burette tip allows an anticipatory feature to be designed into the instrument. With the indicator electrode close to the tip, the control circuit "sees" a region further along on the titration curve than exists in the bulk of the solution. By proper spacing it is possible to make the instrument approach the end point by the introduction of smaller and smaller volume increments of the titrant.

Instruments for the measurement of chlorinity (or related functions)are summarized below:

(1) The Knudsen titration is the standard method for chlorinity determination. It can be carried out on shore or on shipboard, but cannot be readily modified to in situ measurements. Although usually performed with specially designed Knudsen burettes and pipettes, the titration can be done, with no loss in accuracy or precision, with conventional type laboratory glass apparatus.

(2) Conventional conductimetric methods can be applied to shore, shipboard, and in situ measurements. Special precision electrical equipment is needed for all applications. Cell design and behavior appears to be the limiting factor in the reliability of these measurements, especially when adapted to in situ techniques.

(3) High frequency oscillometric techniques have considerable appeal because of their "electrodelessness" but require the solution of high frequency oscillator design problems before direct chlorinity measurements can be made.

(4) Automatic potentimetric titrations can be conducted at sea and ashore but are not adaptable to in situ measurements. Electrochemical considerations suggest that the sensitivity of these methods can be much greater than that obtainable by other methods. Specialized equipment is needed for automatic titrations but manual potentiometric titrations can be carried out with commercially available apparatus.

## COLORIMETERS AND SPECTROPHOTOMETERS

Colorimetric and spectrophotometric procedures are used for the determination of several of the minor constituents of sea water. To name only a few, methods have been described for the determination of inorganic phosphate, nitrate, nitrite, silicate, as well as for plant pigments and for several metallic ions. The last named usually require concentration of the test substances from a large volume of sample before analysis, a process which will be discussed later. The instrumentation of colorimetric analyses can be very simple, especially when the test color has an absorption peak in the visible part of the spectrum and when only a few samples are to be analyzed at one time. The use of Hehner tubes, in which the column heights of solutions of a test sample and a standard are adjusted until the depth of color in both appears identical by visual inspection, is an example of extreme simplicity. Until recently all colorimetric analyses performed at sea were read with visual comparators or photometers. Wattenberg (1937) describes a simple comparator, constructed on the Hehner tube principle, which is typical of many early seagoing instruments. Mellon (1950) gives a detailed discussion of commercially available instruments but makes no reference to their usefulness under conditions normally encountered at sea.

Despite the simplicity and versatility of most visual instruments, the newer and more expensive photoelectric photometers and spectrophotometers have many advantages to recommend them. When considered as a seagoing instrument, the ability of a photocell or phototube to ignore differences in operators and to give results which are not a function of the concentration of dramamine in the operator are real advantages.

The factor limiting the usefulness of most commercial photoelectric instruments at sea is the method of registering balance, or indicating the optical density of the test solution. Instruments which use the barrier layer type of photocell generally use a sensitive galvanometer for this purpose. These instruments are useless at sea. Vacuum phototubes, on the other hand, can be used with relatively simple D.C. amplifiers and the amplified signal made to swing a more rugged meter. The Beckman Model DU spectrophotometer*, while considerably more refined than is necessary for most routine colorimetric analyses, is of the latter type, and can be used at sea under conditions which make it impractical to carry on the chemical operations which procede colorimetric analyses. Beckman instruments have been used on vessels from the Scripps Institution with only routine maintenance and one has been used by the Chesapeake Bay Institute for over two and a half years with only routine changes of desiccant.

For most colorimetric analyses filter photometers provide adequate control of spectral band width. Interference filters can be purchased which will give a band width of approximately ± 10 mμ with peak transmission at any specified wave length in the visible.** However, the analysis of multi-component systems, such as the analysis for several plant pigments in a single extract, requires the use of a spectrophotometer in which the wave length of the incident beam is controlled to approximately ±1 mμ. Such control can be obtained by the use of prisms or gratings.

Snodgrass et al. (1953) have constructed a self-balancing photoelectric filter photometer by drastic modification of a Lumetron model 402-E.*** The modified instrument has been named Automatic Servo-Operated Photometer or ASOP. In its original form the Lumetron bucks the output of two photocells onto a sensitive galvanometer as a null indicator. In the modified instrument, the difference in output of the two photocells is chopped and amplified. The amplified signal powers one phase of a two-phase motor which drives a dial (the balancing control on the unmodified instrument) calibrated in per cent transmission and a potentiometer used as a voltage divider across one of the photocells. When the outputs of both photocells appear the same to the amplifier, the drive motor is not energized and the dial indicates the per cent transmission of the solution in the absorption cell. Micro switches on the door of the absorption cell compartment serve as on-off switches for the light source and amplifier input. In operation, one need only place the absorption cell in its compartment, close the door, and read the dial when it has come to balance. Narrow band interference filters can be obtained for any ±10mμ band in the spectral range in which a glass-covered photocell will respond. The instrument will accommodate cylindrical end window type absorption cells up to 150 mm cell path. An ASOP has been used at the Chesapeake Bay Institute for nearly two years and the only maintenance other than routine cleaning has been the replacement of a paper per cent transmission dial by one imbedded in plastic.

---

* - Beckman Model DU Quartz Spectrophotometer, manufactured by National Technical Laboratories, South Pasadena, Calif.

** - Interference filters can be furnished by: Baird Associates, Inc., Cambridge, Mass., Farrand Optical Co., New York, N.Y., and Photovolt Corp., New York, N.Y.

*** - Lumetron Photoelectric Colorimeter Model 402-E, manufactured by Photovolt Corp., 95 Madison Ave., New York 16, N.Y.

Ford (1950) described a photoelectric filter photometer that was designed and constructed especially for use at sea. The instrument has been named Electric Eye Photometer or EEP after the electric eye used as a null indicator. It uses a 100 watt projector bulb and an optical system to form a split light beam, one half of which passes through a lucite rod and the other half through the test solution. The two emergent light beams fall on a pair of matched No. 926 phototubes. The output difference of the phototubes goes through one stage of amplification (type 38 tube) and onto a 6E5 electric eye null indicator. Balance is obtained by moving a logarithmic shaped aperture into the beam passing through the lucite rod. A vernier adjustment used to position the aperture provides the balance reading when the electric eye has been brought to minimum slit. The original design employs absorption cells of 26, 9, or 1.5 cm absorption path. The 26 and 9 cm cells are modified Nessler tubes used vertically with a glass plunger immersed in the test solution to reduce meniscus effects.

With both the 9 and 1.5 cm cells, a lucite spacer columnates the light from the aperture mechanism to the end of the absorption cell. With the 1.5 cm cell, which is square, the instrument is used in a horizontal position. The power supply includes a pair of VR105 voltage regulators, and supply variations from 105 to 130 volts "produce no appreciable errors in the operation of the instrument." The 26 cm cell path is longer than is available in any commercial instrument except the Beckman model DU. The 50 cm Beckman cell, however, requires special attachments and is not convenient to use intermittently with shorter cells.

## CONCENTRATION TECHNIQUES

Most of the dissolved substances in sea water are in such low concentration that they cannot be determined by direct analysis. They must be concentrated before an analysis can be performed. Sverdrup et al. (1946) (Table 36) list forty-four elements as present in solution in sea water. The major constituents, chlorine, sodium, magnesium, sulphur, calcium, and potassium make up 94.2% by weight of the dissolved solids. Each of these can be determined without prior concentration. Of the remaining thirty-eight, thirteen are in the range $10^{-4}$ to $10^{-6}$%, seventeen in the range $10^{-6}$ to $10^{-8}$%, and eight are less than $10^{-8}$%. Of these only a few can be determined without prior concentration. In addition to these inorganic constituents, *in vitro* experiments with phytoplankton organisms are pointing to the importance of micro-quantities of dissolved organic substances in the role of growth promoting and inhibiting agents. Nothing is known of the range of concentration of most of these substances in the sea.

The importance of many of the minor elements in geochemical and biological processes is of course an open question. It may be significant, however, that the presence of several elements in sea water was unknown until found in the remains of marine organisms where they had been concentrated by metabolic processes. Some trace constituents, however, are known to play major roles in marine systems, yet, lacking information about the distribution of the elements in the sea, our understanding of the processes in which they are involved is very limited. For example, sea bottom deposits have been found which contain 15 to 20% manganese, yet our knowledge of how this accumulation takes place from a reservoir of manganese of only a few thousandths of a part per million is incomplete. Vitamin $B_{12}$, known to be produced in excess of their own requirements by some organisms and to be required by others in amounts greater than furnished by their metabolism, contains an atom of cobalt in each vitamin molecule. Cobalt, then, is directly involved in the metabolism of one group of organisms and indirectly, through a $B_{12}$ requirement, in that of another group. Yet, primarily because methods of concentrating cobalt by a factor great enough to bring it into the range required by analytical procedures have not been available, it is not known whether the cobalt requirement of the $B_{12}$ producer organisms is always met in the oceans. Similarly, little is known about the distribution of vitamin $B_{12}$ in the ocean.

To design a single concentrating system that would be useful for all situations obviously is impossible. The differences in concentrations and of chemical behavior of the many inorganic and organic substances that may be of interest suggests that each situation will have to be treated by itself. Nevertheless, a few general requirements for all systems can be stated. Analysis for dissolved organic constituents probably should be carried out as soon after taking the sample as possible to prevent changes in the constituent by bacterial action, etc. Under these conditions the concentrating system should meet the requirements suggested for a seagoing instrument. Two additional requirements seem desirable for most concentrating systems. They are, (1) concentration factors of $10^3$ or $10^4$ should be possible under conditions that will not limit the accuracy and precision of modern analytical methods, and (2) all techniques should provide as complete a separation as possible of the trace substance from the major constituents.

It is possible to speculate on some of the instrumentation problems that will accompany attempts to concentrate various trace constituents. It seems reasonable that most methods will be built around existing techniques with modifications being developed to meet the requirements of marine systems and of seagoing operation.

Ion exchange resins have been widely used in many kinds of separation precedures. The equipment needed in most applications is extremely simple, being little more than glass or plastic tubes packed with the granulated resin, and in some applications a vacuum or pressure pump to force the sample through the column. A promising application of exchange resins in sea water analysis is that of removing inorganic constituents prior to analysis or concentration of certain dissolved organic substances. In order to be non-reactive with the resins, the organic compounds should be non-ionic or capable of being made nearly so, in which case they will pass through the column. Under some circumstances substances retained by the resins can be eluted from the column with appropriate solvents. Samuelson (1953) has summerized the information concerning the uses of ion exchange resins in analytical chemistry. Provasoli and Carritt (unpublished results) used a mono-bed exchange column containing IR-120 and IRA-410 to deionize sea water prior to performing a bio-assay for vitamin $B_{12}$. The separation was necessary as the assay organism had a low salinity tolerance. Chromatographic columns, some of which use commercial ion exchange resins, appear to have many applications to problems in chemical oceanography, especially to the separation and identification of substances with similar chemical properties.

A column technique was developed by Carritt (in press) for the separation of copper, cobalt, zinc, lead, cadmium, and manganese from natural waters, including sea water. The column consisted of granulated cellulose acetate which had been treated with a dithizone-carbon tetrachloride solution. Recovery was good with solutions containing as little as a microgram of test substances per liter, and separation from the major constituents was excellent.

The January number of Analytical Chemistry has since 1949 contained a number of review articles dealing with various aspects of the field. Included are sections on Ion Exchange, Extraction, Chromatographic Separation, and Instrumentation. These reviews are convenient starting points in the search for analytical methods that may have applications to oceanographic problems.

## RADIOCHEMICAL MEASUREMENTS

The instrumentation of radiochemical procedures is not strictly a problem of the instrumentation of oceanographic measurements. However, the applicability of radio tracer techniques to many oceanographic problems, dating procedures which require the measurement of very low level activities of natural radio elements, and the possible application of activation analysis to the determination of trace constituents suggests that the handling and measurement of radioisotopes should be familiar to workers in oceanography.

Kierstead (1952) in a discussion of Application of Radioactivity to Oceanography outlines most of the topics mentioned above and gives a general statement of the kind of laboratory and the instruments needed to carry out the measurements. Goldberg, Walker, and Whisenand (1951) report the results of an ecological study in which radiophosphorus was used to trace the utilization and regeneration of phosphorus by diatoms. The publications of Libby et al. (1949) and more recently of Kulp (1951) describe the measurement of carbon-14 as a method of determining the age of carbonaceous materials.

An interesting calculation indicates the possible utility of activation analysis in oceanographic problems. It can be shown that the residue from approximately 25 milliliters of sea water when exposed to the neutron flux in an Oak Ridge pile for 100 hours will contain a gold activity ($Au^{198}$) having an initial disintegration rate of approximately 6000 dis./min., an activity well within the limits of accurate counting. The concentration of gold in sea water is approximately $6 \times 10^{-6}$ milligrams per kilogram.

## POLAROGRAPHIC MEASUREMENTS

The polarograph has become a useful analytical tool for the determination of many metallic ions as well as dissolved organic substance in concentrations down to approximately $10^{-6}$ molar. Kolthoff and Lingane (1952) and Muller (1951) give a complete account of the polarographic method. Unfortunately, the concentration of most sea water constituents which might be determined polarographically is below this limit. Dissolved oxygen, however, is present in concentrations within the optimum range of operation of the instrument. The precision that can be obtained by this method is greater than can be realized with the usual Winkler titration, especially with solutions of low oxygen content.

The dropping mercury electrode, used in most polarographic procedures, cannot be used on shipboard or in systems in which the sample is in motion. Manning (1940) followed the variation in dissolved oxygen in a lake by mounting a dropping mercury electrode on a stake driven firmly into the bottom. The recording equipment was on shore. Giguere and Lauzier (1945) describe the use of the dropping mercury electrode and both fixed and rotating platinum microelectrodes for the oxygen determination. Muller (1947) describes the use of a platinum microelectrode in a cell in which the test solution is made to flow past the electrode at a controlled rate.

Platinum microelectrodes (or other stable metallic electrodes) are the only electrodes that appear to be applicable to polarographic analyses on shipboard. In the usual polarographic techniques, a D.C. potential is applied to the electrode to achieve concentration polarization. In solutions containing several reducible substances, all may be reduced at the cathode. In the case of sea water, although the principal reducible substances is dissolved oxygen, many of the trace metals will also be reduced but being in extremely low concentrations their reduction will not contribute measurably to the diffusion current of oxygen. Nevertheless, the surface of a micrometallic electrode will gradually accumulate a surface film of these trace metals. The "plated" electrode then will have different properties than the initially clean surface and the calibration of the electrode will be changed.

Olson, Brackett, and Crickard (1949) obtained much improved stability by applying in place of the D.C. polarizing potential, a square wave potential composed of a positive pulse, a shorting period, a negative pulse, and a shorting period, to a stationary platinum electrode.

Carritt (unpublished results) combined the Olson et al. (1949) and Muller (1947) techniques in such a way that a seagoing polarographic instrument for the oxygen determination appears possible. A polarographic instrument with a solid microelectrode can, at least in principle, be adapted to continuous *in situ* measurements of oxygen concentration. In addition, the dependence of the diffusion current on the velocity of flow past the electrode, shown in the Muller technique, suggests that such a device might be adapted to measuring the velocity of water moving by the electrode.

The specificity of a polarographic wave, together with the sensitivity of the method in dilute solutions, offers many advantages for the analysis of concentrates obtained from extraction columns, etc.

## SPECIAL SHIPBOARD DEVICES

Many shipboard chemical procedures can be improved by employing "gadget-type" instruments to perform operations which, on shore, in the absence of a "moving laboratory", present no problem. Useful gadgets of home design and construction can be found in most laboratories, but unfortunately many of them are not described in the literature. *An Automatic Reagent Dispenser for Shipboard Use* was recently described by Wooster et al. (1951). The instrument permits the rapid addition of precisely measured quantities of a reagent to serial analyses. This is the kind of operation that becomes tedious and time-consuming when done at sea with conventional apparatus.

## DISCUSSION: Clifford A. Barnes

I can add little to Dr. Carritt's very able summary of the present trend towards instrumental and *in situ* measurements of chemical properties of sea water. There are a few observations, however, that might serve to emphasize some of his points.

The need for tailoring the instrument or method to fit the particular problem at hand is often overlooked. The quick responding STD and CTI and the CTD of the U.S. Navy Electronics Laboratory are well suited for defining the mass characteristics of shallow inshore waters, where lateral and vertical gradients are large and change quickly as a result of water movement. At a particular location and depth, changes of salinity of as much as a few parts per mille may occur within as many minutes. An instrumental accuracy of a few tenths of a part per mille of salinity is more than adequate to track the movement of these "fronts" between water parcels, and the information immediately available on the oceanographic vessel can be used to guide the search pattern.* Slower conventional techniques using reversing bottles, although affording higher accuracy for a particular impounded sample, may not be any more representative of the surroundings and may be inadequate because of the length of time involved. On the other hand the STD with its limited accuracy is not suited for measuring the detailed structure and temporal changes in the deeper water of inshore basins or the open sea where changes of a few hundredths of a part per mille may be quite significant. Dr. Carritt has stressed the importance of vessel motion and accelerations on instruments taken to sea. Let us also keep in mind that the motions and accelerations within the sea itself may seriously affect the measured values. Both must be considered in tailoring an instrument for a particular seagoing job. Further, greater precision generally means more time required to reach equilibrium, greater instrumental fragility, less stability and considerably greater cost. The equipment should not be expensively "overdesigned" for precision where changing ambient conditions or other variables nullify or seriously cloud the interpretation of the more precise values.

From the operator's standpoint, Dr. Carritt has stressed the need of simplicity in seagoing instruments, and has implied in his statement of a "free hand to serve as an anchor" a greater potential operator fatigue at sea than in the shore-based laboratory. That this greater fatigue is very real can be attested to by all carrying out chemical measurements at sea and particularly those suffering sea sickness. Considering the operator as well as the scientific objectives I would like to amplify the comments on the use of the Wenner bridge to determine salinity. Measurements by the Coast Guard in routine operations at sea show a precision of about ± 0.004 $^{o}$/oo in salinity as reported by Soule and Barnes (1950). In a series of 38 double measurements on Copenhagen Standard water, batch P-15, a precision of ±0.002 $^{o}$/oo was obtained. The accuracy depends largely upon the constancy of the ratio of the conductivity to chlorinity at a given temperature, good temperature control, the uniformity of the slide wire, and the accuracy of the titrations upon which the calibration of the slide wire is obtained. The usual Knudsen titration is less precise than the conductivity measurements, but these can be made in port and the bridge checked over long periods at sea using the Copenhagen Standard water and oil sealed sub-standard sea water.

The latter if suitably stored in five gallon lots has been found to drift at a rate not exceeding about 0.002 $^{o}$/oo salinity per month. Operations at sea are simplified over any titration method in that only one solution, the sea water, is involved in a single measurement and its volume does not need to be precisely measured. Enlisted men of the Coast Guard were trained to run the bridge in a small fraction of the time required to teach titrations; they would carry out measurements in almost any sea conditions, and operator error was almost entirely eliminated. An individual measurement now requires about $3\frac{1}{2}$ minutes but could be cut about 25 per cent by the use of additional cells. Balancing the modified Wheatstone Bridge through the use of a servo system would make the operation automatic to the extent that only the samples would need to be added and removed and the readings recorded. Although, as Dr. Carritt implies, there is need of additional research on the conductivity - chlorinity relationships for different waters, existing information appears adequate as a basis for calculating dynamic topography.

---

* - Editorial note: See comments by Dr. Carritt immediately following.

There is a present trend towards increased use of micro or semi-micro analytical methods for which ever smaller water samples are collected and stored prior to analysis. I would like to emphasize that the collecting and storing of small samples requires special care to insure that the sample is representative of the sea water in question, and that contamination is kept to a minimum. Contamination is largely an interface problem, usually between the water and the air or the impounding container. In similarly shaped containers of the same material, the surface area increases as the square of a linear dimension and the volume as the cube; thus decreasing the dimensions of the container tenfold will increase the potential contamination an order of magnitude. Several instances of difficulty experienced by different activities resulting from the use of smaller screw cap bottles of 60 to 240 ml capacity instead of the conventional citrate bottle of over 300 ml capacity have come to my attention during the past few years. The method of closure has no doubt caused much of the undesirable variability, and this is perhaps particularly the case in using screw top polyethylene bottles. Nevertheless the larger containers are preferable to the smaller for keeping changes on storage to a minimum. For some purposes these changes are of no consequence. It is another example of tailoring the instrument or technique to the job at hand.

DISCUSSION: Dayton E. Carritt

I wish to expand on Clifford Barnes' remarks on my paper. All of his remarks are pertinent and I'm especially pleased to have his comments on the results with the Wenner bridge together with the reference to his paper with Floyd Soule.

Now there is one point raised that I would like to amplify. His comment "An instrumental accuracy of a few tenths of a part per mille of salinity is more than adequate to track the movements of these 'fronts' between water parcels (here he refers to shallow inshore water)....., " I think should be expanded.

For some purposes Dr. Barnes' statement is correct. There are, however, circumstances for which a much greater instrumental accuracy and sensitivity are needed. In the study of turbulence, for example, from which we can expect to learn how different waters get mixed, theoretical approaches require a knowledge of mean values of salinity and velocity as well as terms which involve random fluctuations from the means. In the treatment of mixing and circulation in a coastal plain estuary, Pritchard (1952) developed a salt balance equation in which terms involving the mean product of random velocity and salinity are retained, rather than resorting to the usual substitution of the mean salinity times a coefficient of diffusion. It turns out that salinity observations which are "good to 0.1 $^{o}/oo$" are just good enough to obtain an indirect measure of the random terms. Ideally, we would like a direct measure of these terms. To get this, an instrument with fast response and high sensitivity, one that will look at changes of the order of 0.01 $^{o}/oo$, appears necessary.

Applying the same approach to the open ocean, where the random fluctuations are smaller, it would appear that a fast response instrument that can look at changes of the order of 0.001 $^{o}/oo$ might be necessary.

All of this further emphasizes Dr. Barnes' remarks concerning

"...tailoring the instrument or method to fit the particular problem at hand...." In this case it might be desirable to use two instruments, the first a slow response device to obtain the mean value of salinity with good accuracy; the second, a fast response instrument to obtain the random terms. The second instrument need not have the accuracy demanded of the first, as the mean of its information could be adjusted to fit the mean obtained with the first. By using two instruments it might be possible to eliminate the troubles encountered when one attempts to combine "high accuracy" and "high sensitivity" in a single instrument.

DISCUSSION: Norris W. Rakestraw

I might add, in addition to what Dr. Carritt has said about the automatic chlorinity titrator (ACT) that this instrument has operated satisfactorily on shipboard under actual conditions. It is not affected by the vibration or the roll of the ship and its effectiveness seems to be limited only by the ability of a man to stand up and operate it. Nevertheless, it is not in its final stage of development for some work should still be done to improve the design of electrodes and to make their placement in the slipstream of the beaker less critical. Neither on shore nor shipboard can this instrument be entirely relied upon when operated by inexperienced technicians. It is not yet automatic to that degree.

Modern instrumentation has also contributed to the measurement of pH, which is important in determining the distribution of carbon dioxide and for many other purposes in chemical oceanography. Until rather recently, this measurement was almost always made by the use of indicators, sometimes with very simple colorimetric apparatus. The use of a modern spectrophotometer makes such a measurement very much more precise, but in any indicator method there is always considerable uncertainty as to purity and properties of the indicator. In recent years, the improvement of the glass electrode and of the electronic amplifier circuits with which it is used, has entirely revolutionized the measurement of pH in all fields of application. Nevertheless, pH meters and glass electrodes must be pushed to their highest degree of sensitivity in order to yield results sufficiently precise for the chemical purposes of oceanography. Unless one's results are reliable to one or two in the second decimal place, it is scarcely worthwhile to make any measurement at all. The great difference in temperatures of the samples and the necessity for excluding air in order to prevent loss or gain of carbon dioxide makes such precision rather difficult. But it is possible to overcome this difficulty by constructing long, narrow electrodes and keeping the samples in polyethylene bottles without presence of air until they have reached room temperature. Measurements made under such conditions seem to be about the most satisfactory which we can accomplish at the present time.

Dr. Carritt mentions the reagent dispensers which we have constructed for use in several field methods. These represent a trend which I feel sure is bound to continue, until the time comes when chemical apparatus for use at sea will be totally different from anything that we use in the shore laboratories. Conventional volumetric apparatus, such as flasks, pipettes, and burettes, were never designed to go to sea, We are gradually learning how to eliminate them. Beakers,bottles, funnels, and other measuring apparatus are all now available in plastic material, generally polyethylene, and these are admirably designed for seagoing use. Large carboys holding as much as 50 liters are now available in such material. They are light, do not break, and will keep water silica-free.

The newer types of ultra-filters (such as the ones known as "Millipore" filters) are becoming a useful tool in chemical operations which require filtration. These plastic filter sheets, when used with suction filtration apparatus, make it possible to filter large volumes of water very rapidly and to remove suspended matter down to a fraction of a micron. The filters can be dried, and by the addition of appropriate liquids can be rendered optically clear, so that the whole filter can be placed under a microscope for observing or counting the suspended material. There are many obvious applications of these.

While the tendency nowadays is for the development of complicated and precise instruments which, to be sure, are making available a fund of new information, nevertheless we have to keep in mind that these are expensive and in many parts of the world oceanographers will for a long time be limited to the older methods which use simple, everyday apparatus. In our enthusiasm for automatic and precise instrumentation we must not lose sight of the opportunities for improving old methods.

## REFERENCES: D.E.Carritt

CARRITT, D.E. 1953. "Separation and Concentration of Trace Metals from Natural Waters; Partition Chromatographic Technique". *Anal. Chem. Vol. 25, no. 12. pp. 1927-8.*

FLOM, D.G., and ELVING, P.J. 1950. "A Survey of High-Frequency Oscillators and Their Chemical Application". *Penn. State Coll., Res. Contr. N6onr-26915, Proj. No. NR-055-211, Tech. Rept. No. 2.*

FORD, WM. L. 1950. "Seagoing Photoelectric Colorimeter". *Anal. Chem. Vol. 22, No. 11, p. 1431-1435.*

GIGUERE, PAUL A., and LAUZIER, LOUIS. 1945. "Le Dosage Polarographique de l' Oxygene Dissous Dans l'Eau de Mer". *Can. Journ. Research Vol. 23B, pp. 76-83.*

GOLDBERG, EDWARD D., WALKER, THEODORE J., and WHISENAND, ALICE. 1951. "Phosphate Utilization by Diatoms". *Biol. Bull. Vol. 101. no. 3. pp. 274-84.*

GRUBBS, FRANK E. 1948. "On Estimating Precision of Measuring Instruments and Product Variability". *Journ. Amer. Stat. Assn., Vol. 43, no. 242. pp. 243-264.*

JACOBSON, A.W. 1948. "An Instrument for Recording Continuously the Salinity, Temperature, and Depth of Sea Water". *Trans. Amer. Inst. Elec. Eng. Vol. 67, Pt. 1, pp. 714-22.*

JENSEN, FRED W., and PARRACK, A.L. 1946. "Use of High-Frequency Oscillators in Titrations and Analyses". *Ind. Engr. Chem. Anal. Ed. Vol. 18, pp. 595-598.*

JONES, GRINNELL, and BOLLINGER, GILES M. 1931. "The Measurement of the Conductance of Electrolytes". III. "The Design of Cells". *Journ. Amer. Chem. Soc. Vol. 53, pp. 411-51.* IV. "The Validity of Ohm's Law for Electrolytes". *Ibid. Vol. 53, pp. 1207-12.*

JONES, GRINNELL, and BRADSHAW, BENJAMIN C. 1933. "The Measurement of the Conductance of Electrolytrs". V.A Redetermination of the Conductance of Standard Potassium Chloride Solutions in Absolute Unite. *Journ. Amer. Chem. Soc. Vol. 55. pp. 1780-1800.*

KIERSTEAD, HENRY A. 1952. "Application of Radioactivity to Oceanography". *Woods Hole Oceanographic Institution, Ref. No. 52-31.*

KOLTHOFF, I.M., and LINGANE, JAMES J. 1952. "Polarography". (2nd ed.) *Interscience Publ., New York.*

KULP, J. LAURENCE. Dec. 1951. "Age of Deep Ocean Water". *Lamont Geological Observatory, Columbia Univ., N.Y. Tech. Rept. No. 4. 12 pp.*

LIBBY, W.F., ANDERSON, E.C., and ARNOLD, J.R. 1949. "Age Determination by Radiocarbon Content: World Wide Assay of Natural Radiocarbon". *Science. Vol. 109, pp. 227-8.*

## REFERENCES: D.E.Carritt Cont'd

LINGANE, JAMES J. 1948. "Automatic Potentiometric Titrations". *Anal. Chem. Vol. 20. pp. 285-92.*

MANNING, WINSCON M. 1940. "A Method for Obtaining Continuous Records of Dissolved Oxygen in Lake Waters". *Ecology. Vol. 21, No. 4. pp. 509-12.*

MELLON, MELVIN GUY. 1950. "Analytical Absorption Spectroscopy; Absorptimetry and Colorimetry". *John Wiley and Sons, New York.*

MORGAN, J.L.R., LAMMERT, OLIVE M. "A Review and Investigation of the most desirable techniques for conductance measurements of non-aqueous solutions using non-platinized electrodes". 1923. *Journ. Amer. Chem. Soc. Vol. 45, pp. 1692-1705.*

MULLER, OTTO H. 1947. "Polarographic Study with a Microelectrode Past Which an Electrolyte is Flowing". *Journ. Amer. Chem. Soc. Vol. 69. pp. 2992-7.*

MULLER, O.H. 1951. "The Polarographic Method of Analysis". (2nd ed.) *Chem. Ed. Publ. Co., Easton, Pa.*

MULLER, RALPH H. 1952. "Instrumentation". *Anal. Chem. Vol. 24, pp. 25A.*

OLSON, RODNEY A., BRACKETT, FREDERICK S. and CRICKARD, ROBERT G. 1949. "Oxygen Tension Measurements by a Method of Time Selection Using Statie Platinum Electrode with Alternating Potential". *Journ. Gen. Physiol. Vol. 32. pp. 681-703.*

PARKER, H.C., and PARKER, ELIZABETH W. 1924. "Calibration of Cells for Conductance Measurements". III. "Absolute Measurements of the Specific Conductance of Certain Potassium Chloride XSolutions". *Journ. Amer. Chem. Soc Vol. 46. pp. 312-35.*

SAMUELSON, O. 1953. "Ion Exchangers in Analytical Chemistry". *John Wiley and Sons, New York, 291 pp.*

SHEDLOVSKY, THEODORE. 1930. "A Conductivity Cell for Eliminating Electrode Effectd in Measurements of Electrolytic Conductance". *Journ. Amer. Chem. Soc. Vol. 52. pp. 1806-11.*

SNODGRASS, J.M., CARRITT, D.E., and WOOSTER. W.S. 1954. "An Automatic Servo-operated Filter Photometer". *Anal. Chem. (in press) Vol. 26, p. 249 50.*

SVERDRUP, H.U., JOHNSON, MARTIN W. and FLEMING, RICHARD H. 1942. "The Oceans; Their Physics, Chemistry, and General Biology". *Prentice-Hall, Inc., New York*

TEXAS, A. and M. RESEARCH FOUNDATION. 1952. "Progress Report 15 March 1951 to 14 March 1952. ONR Contract N7onr-487, Project NR 084-004". *pp. 8-9.*

THOMAS, B.D., THOMPSON, T.G., and UTTERBACK, C.L. 1934. "The Electrical Conductivity of Sea Water". *Journ. Cons. Vol. 9, pp. 28-35. Univ. of Calif. Scripps Institution of Oceanography. 1952a.* "The Automatic Chlorinity Titrator Preliminary Report". *SIO Ref. 52-55. 4 pp. 1952b.* "Progress Report, July-Sept. 1952, Contract NObrs-43356, NE120221-6. SIO Ref. 52-67. p. 4.

## REFERENCES: D.E.Carritt Cont'd

*1953a.* "Progress Report on Oceanographic Instrumentation, April-June 1953". *SIO Ref. 53-55. p. 5.*

VON ARX, WILLIAM S. 1947. "A Salinometer for Use in Brackish Water". *Journ. Marine Research Vol. VI. pp. 139-45.*

WATTENBERG, H. 1937. "Critical Review of the Methods Used for Determining Nutrient Sakts and Related Constituents in Sea Water". *Cons. Int. Expl. Mer. Rapports et Proces-Verbaux. Vol. CIII. 33pp.*

WENNER, FRANK, SMITH, EDWARD H. and SOULE, FOYD M. 1930. "Apparatus for the Determination Aboard Ship of the Salinity of Sea Water by the Electrical Conductivity Method". *Bur. Stand. Journ. Research (RP 223). Vol. 5. p. 711-32.*

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1946. "The Determination of Chlorinity by the Knudsen Method (a Translation of "Chloruration par la Methode du Knudsen" by Mieczylaw Oxner and a reprint of "Hydrographical Tables" by Martin Knudsen). *Woods Hole, Mass.*

WOOSTER, WARREN S., CARRITT, DAYTON E., and ISAACS, JOHN D. 1951. "An Automatic Reagent Dispenser for Shipboard Use". *Journ. Marine Research Vol. X. pp. 194 6.*

# METHODS OF EXPLORING THE OCEAN FLOOR

Robert S. Dietz

## INTRODUCTION

Oceanography is the geoscience which is concerned with the hydrosphere plus the water-air interface and the water-lithosphere interface. The subject of this paper is the instrumentation for studying this last-named interface -- the sea floor. In order to restrict the subject matter, discussion will be limited to those methods which are used to study the sea floor in a strict sense and not those which are used to study processes acting on or along the bottom such as bottom-mounted current meters, turbidity meters, suspended load samplers, etc. Also, it will be limited to devices which can be used in moderate to deep water thus eliminating from consideration such shallow water devices as bottom augurs, pile-driver corers, etc., which belong to the stiff-handled group of bottom samplers to which energy can be applied at the surface. This also will exclude those devices which require operation by a diver.

Methods of exploring the bottom can be conveniently divided into three groups, viz.: (1) direct sampling of the bottom, (2) obtaining bottom information acoustically, (3) visual examination.

## DIRECT SAMPLING OF THE BOTTOM

General - Omitting apparatus for specialized purposes, most bottom samplers can be classified as corers, dredges, grab samplers, and underway samplers. These are the standard or "classical" methods of studying the bottom. Considerable progress has been made in such methods since the subject was summarized by Hough (1939). Hough's paper contains an excellent list of references.

Coring - Various methods of supplying energy to core barrels have been attempted, such as using explosive charges, but to date none have proved as successful as simply using the freefall or dead drop of a heavily weighted core tube. The early types of corers were small and of light weight so that they rarely obtained a core more than a few feet in length. By increasing the weight, using an optimum core tube diameter, and making various other changes Emery and Dietz (1941) were able in 1940 to take cores up to 17 feet long representing a 25 foot section of the sea floor with a 600 pound core tube. This represented about the maximum length of core that could be obtained with a simple gravity corer because the wall friction of the sediment plug in the core barrel prevented any additional material from entering the tube. Hvorslef and Stetson (1946) made additional improvements, one of which was the addition of a tripping arm which allowed the free fall of a corer lowered slowly to the bottom.

Kullenberg (1947) made a great improvement on corers by having the core tube fall over a piston. This keeps the nose of the tube from becoming plugged with sediment and taking on the characteristics of a solid rod. With a piston corer, cores up to almost 70 feet have been obtained and cores 40 feet long can be obtained routinely. Simplified versions of the Kullenberg corer have been made by Ewing and associates, by Frautschy, by Silverman (1952), and by Whaley, and by others. The Lamont Geological Observatory group have been especially successful in making deep sea coring a highly perfected and routine technique, having collected cores, with a total length of about 2 miles, from the Atlantic sea floor. A comparable effort is required in the Pacific Basin and the Scripps Institution of Oceanography has initiated such a program.

The value of cores lies in the relatively undisturbed nature of the sample and especially because they are samples normal to the surface of deposition so that successively older strata are obtained as a function of depth. Sedimentary strata are commonly referred to as pages in a book from which the earth's history can be deciphered. It is evident that deep sea basins hold a much more complete and uninterrupted sedimentary sequence than the continental sedimentary strata. However, major changes in the terrestrial environment are probably required before there is a change in deep sea sedimentation. Much effort should be expended in getting increasingly longer cores of the sea floor. This must eventually involve lowering some source of energy to the bottom along with the coring device. Perhaps rotary coring is the ultimate objective. Fortunately one can anticipate that even the older sediments will be only slightly consolidated.

Grab and Underway Samplers - Grab samplers or snappers are designed to take a surface sample of the bottom. A large variety of this kind of sampler has been devised. They differ largely in the size of sample they will take and in the method of tripping this device upon bottom contact. Actuation of the snapper is generally done either by a slack wire release as in the Peterson grab, or by a foot-type trip as in the NEL snapper (1947). The jaws are generally closed by weights or by being spring loaded.

Snappers are never 100% efficient. If not carefully designed and used, they often fail to trip or trip prematurely -- the latter is especially true of slack-wire releases. If stony bottom is encountered, the snapper is frequently held partially open by a pebble caught in the jaws. In deep water, when such failures are costly of time, it is often advisable to lower a bracket which will hold 2 or 3 snappers so that the failure of one snapper is not serious.

Underway samplers are a special type of grab sampler designed to obtain a bottom sample from a ship underway at normal speeds. Two such devices are Worzel's (1940) "BT sampler" and Emery's and Champion's "Scoopfish" (1948). Such samplers effect a great saving of ship's time and they permit a more accurate dead reckoning track to be run. The sample can also be taken without interfering with the ship's normal routine. They can be used down to at least 75 fathoms which is sufficient for sampling continental shelves.

Pratje (personal communication) of the German Hydrographic Institute has recently designed a new version of an underway sampler which is reported to have been used very successfully in the North Sea. It can recover about a cupful of sediment, which is a much larger amount than that obtained by previous samplers. A copy of this sampler has been made at the U.S. Navy Electronics Laboratory. A preliminary evaluation shows it to be an excellent one.

Dredges - Dredging, in the sense of the word used by marine geologists, means dragging a sampler along the bottom to collect especially the gravel and larger material along the path of the device. The deep sea rock dredge is generally a chain bag attached to a rectangular metal frame. Netting can be inserted in the dredge and the size of the net opening will determine the size of material retained by the dredge. Small pipe dredges can be towed behind the dredge to pick up a sample of the fine sediment. Although dredging is a powerful technique for qualitatively studying the bottom, it is a poorly developed method. Actually no important progress has been made since the Challenger Expedition. We still have no clear idea as to how the dredge is acting on the bottom, how efficiently the dredge is sampling the bottom, whether or not the dredge is spilling its load or how long to tow the dredge along the bottom before pulling it up.

It is commonly stated or implied that a dredge can only sample the most recent deposits. However, it has become increasingly apparent that the sea floor is not everywhere a depositional surface. In many places it is erosional or non-depositional -- thus, old formations outcrop along the bottom. This was clearly demonstrated by the dredging of Cretaceous coraliferous limestones on the Mid-Pacific Expedition. Dredging the fault scarps on the sea floor such as the Mendocino Escarpment seems an especially promising method of penetrating the earlier sedimentary history of the oceans. Such an approach probably will yield more results than attempting to reach the older formations by coring in the sedimentary basins.

Winches, Wire Rope, etc. - Success in sampling the bottom depends as much upon the characteristics of the winch, wire rope, etc., as it does upon the sampler. For example, the BT winch with its small wire (and resultant small water drag), its free spooling, and its rapid breaking and clutching has made possible the use of underway samplers. Also, the success of the heavier piston coring devices necessitates winches of special design. Only in recent years have reliable winches been designed for handling the heavy end loads encountered in coring and dredging. The winch used on the Albatross and the Galathea Expeditions is a good example.

The subject of wire rope is too involved to be treated here. Suffice it to say that any improvements in the tensile strength, corrosion resistance, resistance to unlaying, etc., will be of great benefit to oceanography. Coring and dredging place great loads on wire rope so that it is often difficult to stay within the elastic limit of the wire.

Although sea water is a good conductor of electricity, wire ropes are even better conductors so it is possible to project some electric energy for a considerable distance along a non-insulated wire rope. It seems that some use could be made of this property.*

There is often much difficulty in determining when a sampler reaches the bottom because of the great weight of the wire rope as compared to that of the sampler. Even with a dynamometer to measure cable strain it is necessary for the end load to be at least 20 percent of the gross load. The development of a more sensitive but damped oceanographic dynamometer is much needed. For determining bottom contact, the Scripps "ball-buster" is a promising development. This device, which can be attached to a corer or a grab sampler, implodes a glass ball on bottom contact by a slack-wire release allowing a weight to fall breaking the ball. The resultant sound signal can be picked up by a hydrophone at the ship. Use of a recorder has been helpful in positive identification of the signal. However, as yet the proper functioning of this device is too uncertain to place complete reliance on it.

---

* - Editorial Note: Apparatus utilizing this principle was initiated at Scripps in 1949 and the preliminary results were very encouraging. Additional work has just been reviewed. (November, 1953)

## ACOUSTIC METHODS OF EXPLORING THE SEA FLOOR

The classical method of obtaining information on the nature of the sea floor by direct sampling is now being supplemented by information obtained by means of various types of radiation. Fortunately, water is an excellent medium of transmission of sound. In fact, of all the geophysical methods, those using underwater sound are the most important so that they are the only ones which will be discussed here. Military necessity has promoted the development of the science of underwater sound for detecting and locating underwater targets. The study of the sea floor promises to be greatly aided by the developments in this flourishing science. The recent use of low frequency sound from an explosive source to determine the nature of the crustal layers beneath the sea is a good example but inasmuch as we are concerned here only with method of exploring the water-sea floor interface, we need not discuss this technique here.

Of all devices for exploring the sea floor, the most useful is the echo sounder. This is in spite of the fact that the echo sounder was developed as an aid to navigation and all existing models are still poorly designed as far as being a tool for deep sea exploration and research. An important advance in the echo sounder was made when a recorder was added as in the NMC and the NMC-1 and 2, models which permitted a graphic profile of the bottom to be obtained. Unfortunately, a maximum scale depth of 2,000 fathoms was chosen. Inasmuch as there is little sea floor which lies between 2,000 fathoms and the continental shelf maximum depth of about 70 fathoms, this scale has been of little value. Few graphic records of the deep sea floor have ever been obtained with these echo sounders. In the Pacific Ocean, other than those taken by Scripps and NEL vessels with especially modified equipments, the writer is only aware of the existence of one fathogram in the central Pacific by USS KERSTIN and several in the Gulf of Alaska by vessels of the U.S. Coast and Geodetic Survey.

The recent development of the Edo echo sounder is most promising. The larger paper size, the rectilinear scale, the greater power (apparently sufficient to record the bottom at any depth in the ocean), and the general mechanical and electronic excellence of design are great improvements over the older equipment. However, the paper speed and the choice of scale (on deep scale) are, it seems to the writer, poorly chosen so that the great advantages of this new instrument for exploring the deep sea floor are largely lost. Fortunately, this can be corrected by the addition of second stylus to the stylus belt so that the shoaler scales can be made to record at multiples of the basic scale, e.g., the 0-600 fathom scale then will record at 600-1200 fathoms, etc. Such an alteration will undoubtedly be made on survey and research vessels but it appears that the great mass of detailed bottom data that should come in from the fleet and revolutionize the science of the sea floor, unfortunately will not materialize with the present gear.

Another application of underwater sound to the studying of the sea floor is the determination of bottom type directly from a sound pulse and determination of the structure of the sedimentary layers in the immediate vicinity of the bottom. If such methods can be developed they will be a great boon to the sea floor science. This matter deserves some discussion in this paper. Many persons who have worked with echo sounders feel that they can tell bottom type from fathogram traces and from the audio quality of echo-- but this has more the status of an art than a science. Some of the criteria which seem to be useful for identifying the bottom are (1) topography, (2) echo extension, (3) structure in the bottom echo, (4) the strength of the echo, and (5) audio quality.

The topographic criterion is especially easy to apply to differentiate rock or stony bottom from mud or sand bottom. As a general rule rocky bottom appears to show a rough trace on the echogram whereas sand and mud are smooth. Care must be taken mentally to "filter out" the effect of water waves from the trace. Where there are strong currents, sand bottom is sometimes formed into a series of sand waves or "giant ripples". Such waves are found, for example, in the North Sea near England and along the Atlantic Shelf of the U.S. Here they have an asymetrical wave form with a gentle slope facing toward the current and a steep slope facing down current so that they are readily distinguished from the irregular rough bottom typical of rock. The correlation of roughness of the trace with stony bottom was nicely demonstrated to the writer on a cruise to the Bering Sea where minor roughness characterized the trace. Sampling and bottom photography showed the areas of rough trace consistently to be correlated with stony bottom.

In making a study of the bottom off Point Loma, California, two years ago the writer noted that echo extension characterized the rocky areas. The reason for this is not clear but it is suspected that it is due to irregular bottom with rock facets normal to the incident sound beam and well out on the periphery of the sound cone which reflect sound energy back to transducer at a sufficiently high level to be recorded. If the bottom had been smooth the sound energy would have been reflected away from the source rather than back to it.

The bottom trace on fathograms frequently shows layering or some other type of structure. This is most commonly related to topography which produces side echoes but at other times is related to stratification beneath the bottom. Good examples of this are seen in Murray's (1947) fathograms from the basins of the Gulf of Maine, Hough's from Lake Michigan, from the shelf in the region of the Congo River and from Lake Mead. Penetration of the bottom by sound at the high frequencies used in most echo sounders seems to indicate the bottom is a soft, non-compacted mud because it is likely that compact mud, sand, and rock would permit little penetration.

Regarding the strength of the echo off the bottom, it is known that rock, sand, and mud reflect sound to different degrees. Although there is considerable variation, sand is generally the best reflector of sound, rock is intermediate, and mud is the poorest reflector of sound. Thus, the echo sound appears to offer a useful method of determining bottom type by the criterion of echo strength because the numerous pings tend to average out any variation in the echo strength from a particular bottom. However, although recording papers show some increase in darkening with echo strength, this is slight, so that the technique has not proved very useful. Another technique of determining bottom type by echo strength is to turn the gain high and then to count the number of bottom reflections. A strongly reflecting bottom commonly shows one or two more bottom reflections than others.

## VISUAL METHODS OF EXPLORING THE SEA FLOOR

It is reported that 80% of our information about our environment is derived through the sense of sight. It is also said that more is known about the moon's earth-fixed face than is known about the ocean floor which is much more accessible to all methods of exploration except that of "seeing". This points up the fact that the sea floor will always remain a mysterious environment so long as it cannot be seen.

As a substance, water is a good medium of transmission of light, even though it is a poor medium as compared to air. In the purest sea water one can see as far as 200 feet. Fortunately the bottom water of the open sea almost everywhere approaches this maximum transparency so that here optical methods of exploring the bottom have their greatest value. In shelf waters and especially in harbors and in inland waters, the presence of dissolved "yellow substance" and of organic matter and sedimentary particles greatly reduces "seeing" by absorption and scattering so that in these places visual methods are greatly restricted. Some attempts have been made to partially overcome this poor "seeing" but these to date have not been of much value. It seems likely that the poor "seeing" conditions in shallow water will never find a satisfactory solution but this should not deter one from utilizing visual methods of exploring the deep ocean where conditions are favorable.

Three methods are available to us of examining the sea floor visually. These are: (1) direct observation by lowering the eye to the vicinity of the bottom; (2) use of a remotely operated camera; and (3) underwater television. Lowering the human eye to the vicinity of the bottom is still a shallow water technique so that we need not consider it here. However, in passing, it is worthwhile to point out that the recent development of inexpensive self-contained units such as the aqualung which requires somewhat less experience and ability than the conventional helmet, hose, and suit gear now permits the scientist to explore the bottom depths to at least 100 feet with safety. Attempts to descent to the bottom by such devices as the Benthoscope of Barton and the Bathyscaphe of Picard and Cousyn have not been successful.* Some deep dives into the volume of the sea have been made such as with the Bathysphere and with the Benthoscope but the use of such a device has always been a feat of engineering and of human daring. Such dives have never become routine enough to permit the collection of useful scientific data. There is little doubt, however, that with a moderate expenditure of funds, an undersea craft, capable of diving to the bottom at great depths with a human passenger, could be developed. One can hope that the Navy will some day, in the not too distant future, see its way clear to develop such a craft as a research tool.

Although underwater photography has long been employed in shallow water the first really successful deep sea photography was done during World War II by Ewing, Vine and Worzel (1946) using a self-winding and cocking Robot camera and a flash bulb which were tripped synchronously on bottom contact. Subsequently underwater cameras have been developed and successfully used in oceanographic research at the Navy Electronics Laboratory, at Scripps Institution of Oceanography, at the Hancock Foundation (1952), at Lamont Geological Observatory, and the Woods Hole Oceanographic Institution. Some of the recent developments in underwater photography are: (1) the use of an electronic flash unit which permits a large number of photographs to be obtained during each lowering and which successfully stops all motion; (2) the development of a wide angle underwater lens; (3) the partial development of more intense light source (lack of light rather than absorption or scattering is still the factor limiting range in deep sea photography). Deep sea cameras must have a self-contained power source and be lowered on wire rope until it is proved feasible to lower conductor cable to the deep sea floor.

Although only a few thousand bottom photographs have been obtained to date many significant findings have resulted. A few which have resulted from the work at NEL are, for example: (1) Phosphorite nodules on 30-Mile Bank off California were shown to form an extensive bedded deposit; (2) On the Mid Pacific Expedition, manganese crusts were shown to be covering the rocks of

---

* - Since the original writing of this paper it has been reported in the press that Picard has attained the deep floor of the Mediterranean Sea.

Sylvania Seamount giving evidence of an extensive manganese deposit; (3) Deep ripple marks, scours, etc., have established the existence of currents in the ocean at greater depths than was hitherto known; (4) Much information has been obtained on the ecology of bethonic life; (5) Much information has been obtained on bottom structures such as tracks, burrows, etc., which are useful in establishing paleo-ecologic criteria regarding the depth and environment of deposition of sedimentary rocks. Further work with the camera should reveal the presence of minor erosional forms, such as gullies, and the detailed character of submarine canyons and deep sea channels. It seems to the writer that, in the long run, more information will be obtained on the nature and importance of bottom currents by photographing the bottom than by any method of direct measurement of bottom currents. One also can hope that bottom photography might detect a turbidity current in actual operation.

Finally, with the camera in a watertight housing and the monitor on the deck of a ship, underwater television offers a promising method of exploring the ocean floor. Development of the small industrial model television camera with the Vidicon tube, which permits the use of a small housing, is especially hopeful. Because of line losses and because of the infeasibility of lowering conductor cables to great depths, TV must remain, for the present, a method applicable only to continental shelf depths. Underwater TV was first used in the 1947 resurvey of Bikini Atoll (Engleman) but the great utility of the method was first forcibly demonstrated by the identification of the sunken submarine Affray in the English Channel by the British in 1951.

DISCUSSION: Bruce C. Heezen*

Of the methods of exploring the ocean floor discussed by Dr. Dietz, the ones presently producing the bulk of the useful data are echo sounding, coring, dredging and undersea photography. Most urgently needed in connection with these techniques is the development for general use of accurate echo sounder recorders of high resolution and the development of fast reliable winches which could be available to the major research and survey vessels.

The development of recording echo sounders able to record in depths greater than 2000 fathoms came during World War II with the modified NMC models. More recently the EDO echo sounder has been developed incorporating many electronic improvements. As Dietz has pointed out, the 0-6000 fathom scale of the EDO instrument is of little use to the geologist or hydrographer, and most of us have made the required changes to convert the EDO recorder for multiple 600 fathom scale recording. However, the quality of this type of EDO record is far from satisfactory. It has been found in three recent cruises of the R/V ATLANTIS and R/V ALBATROSS III that the stylus speed of at least two individual sets, when operated on a precision a.c. power supply, is about 2.5% faster than the stated standard velocity of 4800 feet per second. Other errors are caused by stylus belt bounce and by fluctuations of the zero line. Vast flat, nearly level plains have been found in the deeper parts of the Atlantic Ocean and probably occur in all of the oceans. The slopes of these "abyssal plains" probably range from less than 1 to 10 feet per mile. In order to study these areas the development of a sounder which in any depth accurately records to 1 fathom or better is urgently needed. **

---

* - Contribution No. 98 from the Lamont Geological Observatory.

** - Since the Rancho Santa Fe Conference such a recorder has been developed, tested at sea and is now in general use on Lamont Geological Observatory cruises (Luskin, Heezen, Ewing and Landisman, in press).

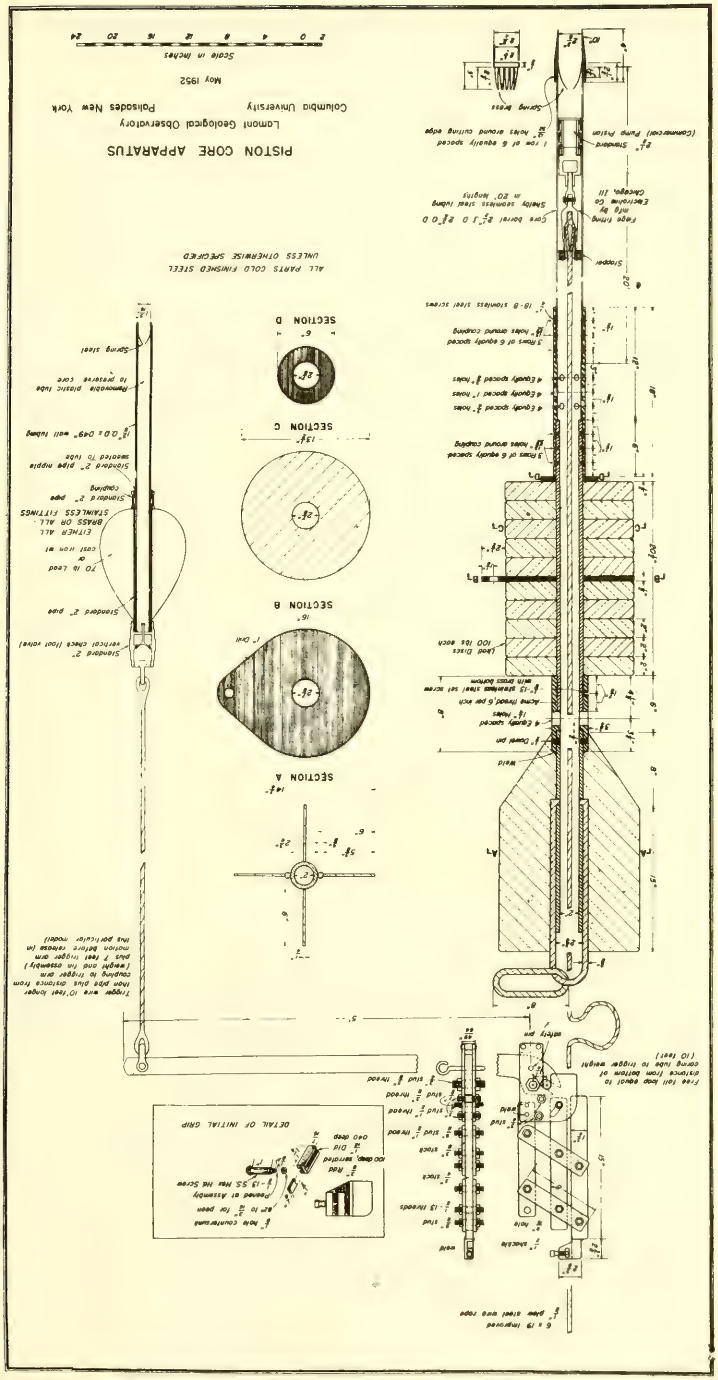

6 x 19 Improved
1/2" plow steel wire rope
1/2" shackle
9/16" hole
15"
weld
3/8" stud
1/2 - 13 threads
3/4" stock
3/8" stock
3/8" stud 1/2" thread
3/8" stud 1/2" thread
1/2" stud 3/8" thread
1/2" stud 3/8" thread
49/64"
Free fall loop equal to distance from bottom of coring tube to trigger weight (10 feet)
safety pin
5'
8"
1/8" hole countersunk
82° to 3/16" for peen
Peened at Assembly
1/2 - 13 S.S. Hex Hd Screw
3/8" Rdd
.100 deep, serrated
1/16" Dia
.040 deep
DETAIL OF INITIAL GRIP
Trigger wire 10'feet longer than pipe plus distance from coupling to trigger arm (weight and fin assembly) plus 7 feet trigger arm motion before release (in this particular model)
A
15"
8"
Weld
1/4" Dowel pin
4 Equally spaced 1 1/4" Holes
Acme thread, 6 per inch
1/2"-13 stainless steel set screw with brass bottom
Lead Discs 100 lbs each
B
C
D
20 1/2"
3 Rows of 6 equally spaced 13/32" holes around coupling
4 Equally spaced 3/4" holes
4 Equally spaced 1" holes
4 Equally spaced 3/4" holes
3 Rows of 6 equally spaced 13/32" holes around coupling
1/4" 18-8 stainless steel screws
18"
12"
20'
Stopper
Fiege fitting mfg by Electrohme Co Chicago, Ill
Core barrel 2 1/2" I D 2 7/8" O D
Shelby seamless steel tubing in 20' lengths
2 1/2" Standard (Commercial) Pump Piston
1 row of 6 equally spaced 13/32" holes around cutting edge
Spring brass
10°
SECTION A
14 1/2"
SECTION B
16"
1" Drill
SECTION C
13 1/2"
SECTION D
6"
Standard 2" vertical check (foot valve)
Standard 2" pipe
70 lb Lead or cast iron wt
EITHER ALL BRASS OR ALL STAINLESS FITTINGS
Standard 2" pipe coupling
Standard 2" pipe nipple sweated To tube
1 5/8" O.D x .049" wall tubing
Removable plastic tube to preserve core
Spring steel
ALL PARTS COLD FINISHED STEEL UNLESS OTHERWISE SPECIFIED
PISTON CORE APPARATUS
Lamont Geological Observatory
Columbia University
Palisades New York
May 1952
Scale in Inches
2 0 4 8 12 16 20 24

Fig. 1. Piston Core Apparatus

Frautschy has described at this conference the details of the design of a new, exceptionally promising winch which is being developed at the Scripps Institution. The importance of a fast, reliable winch cannot be overemphasized, for on its reliable performance the success of the entire sampling program is dependent. The winch should be relatively fast. Ships' time is extremely expensive, and inexpensive slow winches can soon become very costly by viture of the excessive time they consume. The day should soon come when a core can be taken in any depth in an hour or less. Over 90% of the more than 600 deep sea cores in the Lamont Geological Observatory collection were obtained during short periods of spare time on cruises made for other purposes. Faster, more reliable winches could have multiplied this figure. All oceanographers have experienced winch breakdowns or seen the wire part with valuable gear over the side. Heavier better designed winches which take better care of the wire could cut down the occurrence of such disasters. It is conceivable that in the near future heavier instruments such as heavier cores, heavy robot drilling rigs or other weighty gear may be developed. It is therefore desirable that winches using heavier tapered cable be developed; winches which would use heavier wire than the presently used 3/8" to 3/4" sizes.

In 1948 Professor Maurice Ewing and Mr. Angelo Ludas of Columbia University modified a Hvorslev-Stetson free-fall corer to use tubes of greater diameter ($2\frac{1}{2}$" diameter) and to take a piston according to the principle described by Kullenberg (1947). In subsequent years they have further improved and modified the instrument. Figure 1 is a drawing of this apparatus as constructed at present. Figure 2 (modified Hvorslev, 1949) diagrammatically shows its operation. From the experience of using the piston corer to obtain over 600 cores (figure 3) in the North Atlantic it has been modified and improved until now it is an efficient, convenient instrument. One of these improvements is the wire clamp by which the tripping mechanism is attached to the main trawl wire. Before the addition of this clamp a serious problem was encountered in getting the apparatus aboard after it was brought back from the ocean floor since the coring head was hanging about 60 feet below the tripping device on a separate wire. Now all that is necessary is to remove the clamp and winch in the wire.

Telling when instruments are on bottom is extremely difficult and often next to impossible. With the free-fall corer this problem is usually not serious. As long as the core trips properly and the dynamometer is working, even in very deep water an experienced man can have little doubt when contact is made. A careful observer can observe the tripping of a free-fall core if the weight of the the core equals or exceeds approximately 10% of the weight of the wire. Figure 4 is a reproduction of a tension vs. wire paid out plot of a type made on each lowering on Lamont Geological Observatory cruises. A great advantage of the free-fall core is the sharpness of the contact signal made by the momentary release of the entire weight of the core from the trawl which sends a jerk up the wire. This principle might be employed in other gear such as dredges where the release of the weight might serve no other purpose than to produce the contact signal. The length of the cores taken with the 1000-lb. rig (figure 3) varied from chips of rock or a few inches of stiff clay to 50 feet in softer sediments. Important advances may be made by taking longer cores. The fact that the penetration of a 40-ft. coring tube driven by a 1000-lb. weight is often only a fraction of the tube length indicates that a heavier weight is needed to increase penetration. This requires heavier trawl wire and heavier winches since the winches in use on most research vessels cannot handle appreciably greater loads. In the localities where 40-50 foot cores have been taken (northern Gulf of Mexico, upper continental rise off New England, the Azores plateau, etc.) it is likely that cores may be taken up to and perhaps exceeding 100 feet with the present 1000-1500 lb. rigs. Indications are that these localities are ones of rapid sedi-

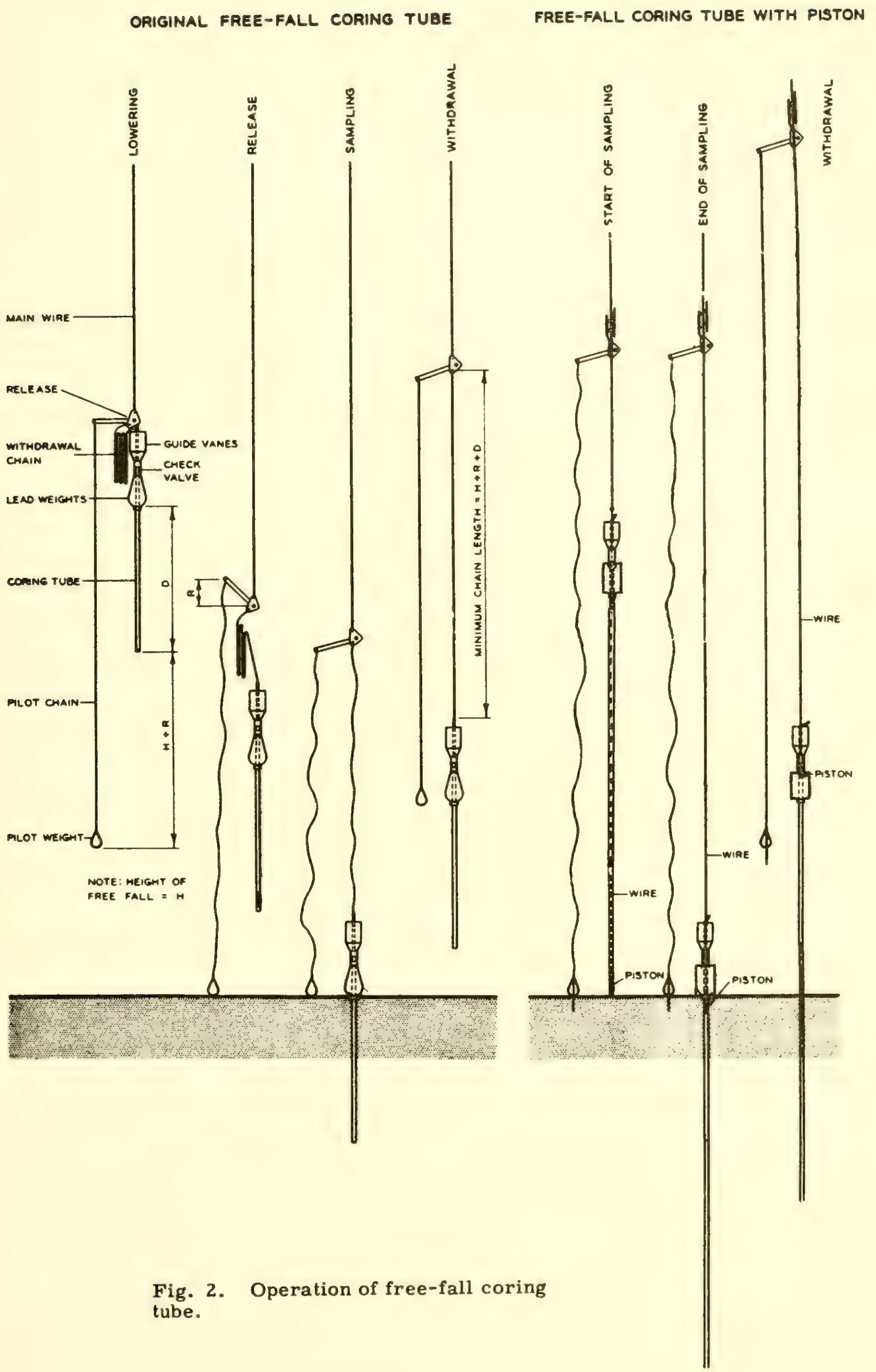

ORIGINAL FREE-FALL CORING TUBE
FREE-FALL CORING TUBE WITH PISTON
LOWERING
RELEASE
SAMPLING
WITHDRAWAL
START OF SAMPLING
END OF SAMPLING
WITHDRAWAL
MAIN WIRE
RELEASE
WITHDRAWAL CHAIN
GUIDE VANES
CHECK VALVE
LEAD WEIGHTS
CORING TUBE
D
R
PILOT CHAIN
H+R
PILOT WEIGHT
NOTE: HEIGHT OF FREE FALL = H
MINIMUM CHAIN LENGTH = H+R+D
WIRE
PISTON
WIRE
PISTON
WIRE
PISTON

Fig. 2. Operation of free-fall coring tube.

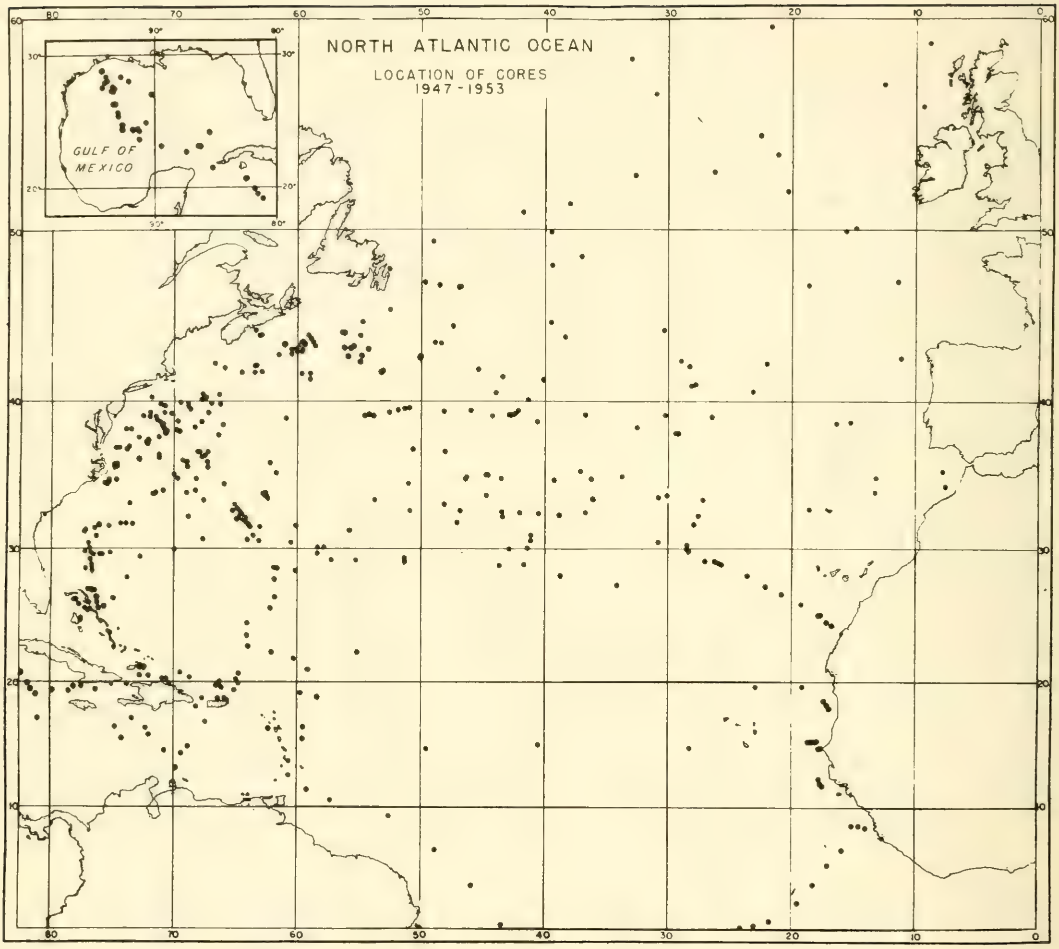

NORTH ATLANTIC OCEAN
LOCATION OF CORES
1947-1953
GULF OF MEXICO
90°
80°
30°
20°
80
70
60
50
40
30
20
10
0
60
50
40
30
20
10

Fig. 3. Plot of coring stations in North Atlantic, 1947-53.

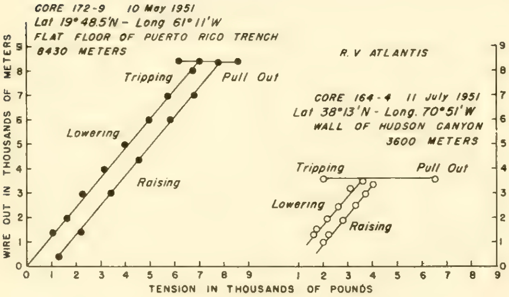


Fig. 4. Typical plot of wire tension during coring.

mentation and the recovered longer cores may not extend back through any greater time sequence than some of the shorter cores from other localities.

The introduction of radiocarbon dating of carbonate sediments requires the development of a large diameter coring tube in order that larger volumes of sediment may be sampled from each horizon. At present the size of the sample needed requires that several inches of the $2\frac{1}{2}''$ diameter core be used. This has obvious disadvantages since no single layer can be dated. The major problem of design in the construction of a 12-24 inch diameter core is the core retainer or core catcher to prevent the core from dropping out of the tube. These large diameter cores might help in the interpretation of ocean bottom photographs because of the large area of ocean floor sampled.

No entirely satisfactory underwater camera has yet been built but indications are that the multiple shot electronic flash cameras under development in several laboratories will soon fill this need. A camera designed by E. M. Thorndike of Lamont Geological Observatory and Queens College has been tested and is very close to an efficient, reliable design.

The short core attached totthe bottom of the pole supporting the single shot camera often gives invaluable clues for the interpretation of the photographs. With the advent of the multiple shot camera the design of a multiple bottom sampler is required in order that the same information be obtained.

Professor Ewing and the writer made a study of the destruction of submarine cables following the Grand Banks earthquake (Heezen and Ewing, 1952). This study produced indirect evidence on the transportation of sediments on the sea floor by means of a turbidity current. Although such natural experiments are disasters to the cable companies they give us important information about the ocean floor.

The importance of having adequate winches overshadows the other needs in both urgency and cost of individual installations. There is little point in developing better gear only to be lost on a faulty winch or to be not used because of the prohibitive time taken by a slow winch. Research vessels and naval vessels are accumulating echograms taken along hundreds of thousands of miles of track but because of lack of precision recorders much of this material is of little use. The easiest way to make an advance in submarine topography is to stop this appalling waste by the installation of more precise depth recorders on all naval vessels and research vessels.

DISCUSSION: Jeffery D. Frautschy

Dr. Dietz has pointed out the importance of satisfactory wire rope operation to successful sampling, but has not dealt in detail with the matter, considering it to be too involved. In the light of the importance of this subject it is felt that a brief discussion is in order.

Until very recently most oceanographic organizations have used wire rope in the size of 3/32 inch to 3/8 inch having a 7 x 7 or 7 x 19 construction. This is usually listed as "aircraft cord". It consists of seven strands identical in section, each section containing 7 or 19 wires as the case may be. Six of the strands are laid in a helix around the core strand, the direction of rope lay being opposite to the direction of strand lay. It is readily apparent that the six outer strands are longer than the core strand. In the case of most aircraft cord this difference amounts to about 5 percent.

Examination of a number of lengths of oceanographic wire rope that had been retired from service revealed that in most cases retirement resulted from mechanical damage rather than corrosion. The type of mechanical failure most often observed seems to result from stretching the core strand beyond its elastic limit. Tests were made to determine the behavior characteristic of seven strand cable which results in this excessive loading of the core.

A test length of 3/16 inch diameter 7 x 19 aircraft cord 75 feet in length was suspended from the top of a tower. A load of 1500 pounds was suspended from the free lower end of the cable and permitted to rotate. When rotation stopped and equilibrium was reached the cable had unlaid 320 turns and had lengthened 16 inches. Repeated applications of the same load resulted in additional unlaying and elongation each time. This elongation caused by rotation results in subjecting the core to far more than its designed share of the total load and results in its eventual destruction. This occurs because the outer strands accomodate themselves to the increased length by assuming a lay helix of larger pitch. On the other hand the already shorter core strand is twisted even tighter by the lengthening of the rope lay. This permits the core to lengthen only by tensile elongation and yield of its component wires.

To avoid this kind of design deficiency a coreless three-strand wire rope was constructed and tested in the same way. In contrast to the test record of the seven-strand wire, the three-strand wire made only 40 turns and was elongated only two inches under the initial loading. The amount of rotation and elongation diminished with repeated loadings until a condition of equilibrium was reached.

As a result of these tests hydrographic winches on Scripps Institution of Oceanography vessels have been equipped with 3/16 inch 3 x 19 wire rope. This cable has functioned satisfactorily and has a much greater life than seven strand cable of the same material. It appears that now most cable retirement will result from corrosion damage. One length of 3/16 inch 3 x 19 cable of galvanized improved plow steel has been in service more than 18 months. It should be pointed out that the larger wires with thicker zinc coatings of this cable have greater corrosion resistance than the relatively small, thinly clad wires of the 7 x 19 aircraft cord. It is true that there has been a sacrifice of some flexibility, but this does not appear to be an important loss.

Tensile tests of the 3 x 19 cable have shown it to be as strong or stronger than comparable aircraft cord. Cost of the new cable is about 60 percent of the cost of aircraft cord of the same diameter and quality.

## DISCUSSION: Roger Revelle

The desire to take as long a core as possible is a very natural one, for what lies far beneath the sea floor challenges both the imagination of the geologist and the ingenuity of the inventor. But in the design and use of bottom sampling equipment the objectives of investigation should be kept in mind. Consideration of these objectives indicates that an ideal coring device should:

1. Take as long a core as possible.
2. Cover as large an area as possible.
3. Disturb the sediments and the overlying water as little as possible.
4. Collect any kind of material on the bottom, be it mud, sand or rock.
5. Record or preserve the original orientation of the material.

No corers have yet been developed which fulfill all these requirements and the aim of most designers has been to satisfy only one of them. Consequently it is necessary to use several different collectors to obtain satisfactory samples for different purposes.

The student of foraminifera is concerned, among other things, with the relative numbers of living and dead benthonic foraminifera on the bottom surface, and he needs undisturbed samples of the topmost few millimeters. The ecologist wants a census of the numbers of living creatures per unit area; because most biological activity takes place in the upper layers of the sediments, he needs a large, undisturbed sample, covering a known area, of these upper layers. The chemist needs samples, uncontaminated by stirring of the bottom mud, of the water immediately above the bottom, in addition to comparatively undisturbed samples of the sediments from the surface down to as great a depth as possible. The bacteriologist needs a core of sufficient dimension so that he may dissect out an uncontaminated sample, and he requires that the sediments near the surface be undisturbed because this is the zone of most intense microbial activity.

In order to study rates of sedimentation it is necessary that the sediments at different depths below the bottom surface be equally represented in the sample. The use of carbon-14 and other similar methods for age determination requires a large-diameter core which can be dissected into thin layers, yet provide enough material for analysis.

In studying laminations and bedding structures, we need to know the lateral variability. One of the ways in which this can be accomplished is by taking multiple closely spaced cores, for example by the use of two or three gravity corers rigidly attached in parallel as a "bident" or "trident".

Few effective coring devices are equally effective in mud, sand and rock. A corer which takes a long undisturbed sample of silt or clay will often not retain sand, and will usually be brought up without a sample, but badly damaged, on striking rock. No devices presently available to oceanographers can be depended upon to recover a long undisturbed core of sand or an oriented sample of rock outcropping on the sea floor. The problem of rock sampling beneath an overburden of unconsolidated sediments has been partly solved by oil companies exploring the continental shelf. A hole is jetted through the overburden with hose and pumps, and a short core of the underlying rock, with orientation recorded, is obtained.

In many cases it is desirable to obtain a large sample of one or more of the constituents of the sediment. This is the purpose of such devices as the bottom trawl and the Isaacs-Kidd "diving dredge", which separate out and collect the larger organisms living on the sea floor, and such large-sized inorganic components as rock pebbles and manganese nodules.

Core samples brought back to the laboratory can be studied in many ways. Several books have been written on this subject and new techniques are constantly being developed. Time and space do not permit even a brief review but it may be sufficient to refer to the superb results obtained by Arrhenius, Pettersson and their co-workers through the coordinated use of different techniques - biological and mineralogical examination, chemical, x-ray, spectroscopic and mechanical analysis, and determination of physical properties - on the more than 5,000 feet of cores collected on the Swedish ALBATROSS expedition. Their work shows that long cores of deep sea sediments can constitute an archive of events in the ocean during the last million or more years, and as such merit the same careful handling as a good librarian gives to the books under his charge.

The taking of long cores in the open deep sea is expensive, costing roughly $100 per lineal foot. But this expenditure is partly wasted if the cores are not properly treated after collection so as to preserve, in so far as possible, the original water content, and to prevent chemical changes accompanying increased bacterial activity. Cores of red clay, for example, shrink as much as 75% on drying, and structures become almost unrecognizable. On our earlier expeditions we attempted to retain portions of the sediment chemically unchanged by placing them in sealed mason jars, without addition of water or preservative. Samples treated in this way show little change in water content or chemical properties even after several years, but bedding and other structures are lost. Our present technique is to wrap three-foot sections of the corers in a thin sheet of cellophane or other plastic material, which is held in shape by plastic discs at each end and sealed with scotch tape. This cylinder is then placed in a cardboard mailing tube having a rather snug fit. This in turn is enclosed in wrapping paper, sealed with tape, and dipped in molten tropic wax. The wrapped core sections should be placed as soon as possible in an ice box at a temperature of about $0^{\circ}$ centigrade. We are constructing a core storage room, capable of holding 12,000 feet of cores, which can be kept saturated with water vapor at a temperature just above freezing.

In addition to bottom samplers, other instruments are needed to determine in situ the properties of the bottom and the sediments, and the processes taking place on or under the bottom. The deep sea lead, the oldest of all oceanographic instruments, is a device for determining bottom properties, as is its lineal descendent, the recording echo-sounder.

More recent examples of this kind of instrumentation are the bottom temperature gradient probes developed by Bullard, Maxwell, Snodgrass and Isaacs. The type used at the Scripps Institution consists of a hollow steel spear 10 feet long and 1.64 inches in outside diameter, in which thermistors are mounted near each end. The spear is attached at its upper end to a water-and pressure-tight chamber, within which is a battery-powered, self-balancing, null-type potentiometric recorder. From a 30-minute continuous record of the temperature difference between the two thermistors it is possible to deduce the undisturbed temperature gradient in the sediments. A core is obtained at the same station, and samples of the sediments are carefully preserved for laboratory determination of thermal conductivity. The product of the conductivity and the temperature gradient gives the heat flux through the sea floor. The probe and recording assembly are illustrated in the frontispiece. Developments are underway to determine the thermal conductivity in situ as well as the temperature gradient.

Measurement of variations in the electrical potential between the supernatant water and the sediments, and in the amount and size of colloidal particles suspended in the supernatant water, either by direct sampling or by turbidity measurements, are examples of the study of sedimentary processes.

Many attempts have been made to develop sediment traps to measure the present rate and character of deposition. A perfect sediment trap must not interfere with the normal processes of sedimentation and yet must be capable of collecting deposited material. The first requirement means that the sediment trap must look to the water and the bottom as if it were not there, the second that it must retain the sedimentary material which reaches it, and these two requirements are so nearly incompatible that no sediment trap built to date has been more than partly successful.

## REFERENCES: Dietz

EMERY, K.O. 1952. "Submarine Photography with the Benthograph". *Science Monthly. Vol. 75, no. 1, pp. 3-11*

EMERY, K.O. and CHAMPION, A.R. 1948. "Underway Bottom Sampler". *J. Sediment Petrol. Vol. 18, no. 1, pp. 30-33.*

EMERY, K.O. and DIETZ, R.S. 1941. "Gravity Coring Instrument and Mechanics of Sediment Coring". *Bull. Geol. Soc. Am. Vol. 52, pp. 1685-1714.*

ENGLEMAN, C.L. 1948. "Underwater Television". *Electronics. Vol. 21, no. 2, pp. 78-80.*

EWING, M., VINE, A. and WORZEL, J.L."Photography of the Ocean Bottom". *J. Opt. Soc. Am. Vol. 36, no. 6, pp. 307-321.*

HAMMOND, R. 1952. "Can the Television Camera Help World Fishing?". *World Fishing. Vol. 1, no. 1, pp. 20-25.*

HOUGH, J.L. 1939. "Bottom-sampling Apparatus". *Recent Marine Sediments, A Symposium. Am. Assoc. Petroleum Geol. Tulsa, Okla. pp. 631-664.* 1952. "Fathogram Indications of Bottom Materials in Lake Michigan". *J. Sediment Petrol. Vol. 22, no. 3, pp. 162/172.*

HVORSLEV, M.J. and STETSON, H.C. 1946. "Free-fall Coring Tube: a New Type of Gravity Bottom Sampler". *Bull. Geol. Soc. Am. Vol. 57, pp. 935-949.*

KULLENBERG, B. 1947. "The Piston Core Sampler". *Scenska Hydrografisk-Biologiska Kommissionens, Skrifter, Tredje serien, Hydrografi. Bd. 1, Hafte 2, pp. 1-46.*

LAFOND, E.C. and DIETZ, R.S. 1948. "New Snapper-type Sea Floor Sediment Sampler". *J. Sediment Petrol. Vol. 18, no. 1, pp. 34-37.*

MURRAY, H.W. 1947 "Topography of the Gulf of Maine". *Bull. Geol. Soc. Am. Vol. 58, pp. 153-196.*

SILVERMAN, M. and WHALEY, R.C. 1952. "Adaption of,the Piston Coring Device to Shallow Water Sampling". *J. Sedi. Petr. Vol. 22, no. 1, pp. 11-16.*

WORZEL, J.L. 1948. "Ocean Bottom Sampler for Ships Underway". *Geophysics. Vol. 13, no. 3, pp. 452-456*

# AIR-SEA BOUNDARY PROCESSES

Walter H. Munk

## INTRODUCTION

From a cause-and-effect point of view, nearly all subject matters that have been discussed during this symposium can be traced eventually to a transmission of energy, in one form or another, through the air-sea boundary. Transmission through the sea bottom amounts to only $10^{-4}$ of that through the surface. If the surface boundary were impervious to energy transmission, there could hardly be any motion in the sea, and there could certainly be no marine life. It is therefore worthwhile to know something about the transmission characteristics of this boundary.

## SOLAR RADIATION

Let us start with a simple problem. Solar radiation upon the sea surface is partly transmitted, partly reflected. For normal incidence, about 2 per cent is reflected, for glancing incidence, nearly all is reflected. The dependence of reflectivity on the angle of incidence is given by Fresnel's law. Except for some uncertainty associated with the polarization of the incoming radiation, the reflection coefficient can be computed for any angle of incidence with an accuracy unusual in oceanographical problems. The situation would be altogether satisfactory if the sea surface were flat. But this situation exists only approximately on a calm day, and it is far from true on a rough day. Suppose there is a 30 mph wind, and the sun is 40° above the horizon. Then only half the incoming rays strike the sea surface at angles of incidence between 30° and 50° ; for the other half the angle is either less than 30° or more than 50°. The overall reflection is now different from what it would be on a calm day. The effect of the ruffling is, so to say, a smudging of Fresnel's curve. To compute the reflection of solar radiation, we need to know not only the sun's elevation, but also the wind.

But this is not the only effect of the ruffling of the sea surface. The transmitted light is not a steady uniform light, but varies, depending upon the instantaneous configuration of the sea surface. Relatively low light intensity is interrupted by the bright flashes of caustic lines. It is in this flashing and flickering space, not under the steady radiation of a laboratory lamp, that the photosynthesis of diatoms produces nearly all organic material on the earth.

Since the incoming radiation is so greatly modified by the sea surface, then in turn optical methods should provide a suitable means for studying the geometry of the sea surface. This idea is far from new. In 1820, Spooner, in a letter to Baron de Zach, described his observations of the sun setting over the Tyrrhenian Sea. He reasoned that if the sea were flat calm, there would be a single mirror-like image of the sun on the water. But the fact that there were thousands of highlights implied that little facets on the sea surface were so inclined as to reflect additional rays from the sun toward his eye. He measured the angular width of the sun path, and from this computed by simple geometry that slopes up to 30° were presented. A refined version of this method has been used by Hulbert, and later by Shuleikin, with similar results.

Actually, this method is open to criticism. The choice of the width of the sun path is a somewhat subjective matter, depending as it does on the sensitivity of our eyes. Otherwise, why should the path of moon glitter be narrower than that of the sun? The method can be made quantitative by measuring not the total width of the glitter path, but the change of brightness within the glitter pattern. By the use of such a method, Cox and Munk find that the slopes are nearly normally distributed, with the mean square slope increasing roughly linearly with the wind speed, and that, as a first approximation, the slopes are the same in all directions. Surface slicks reduce the slopes by a considerable amount.

## LABORATORY EXPERIMENTS

These results have a bearing on laboratory methods for studying the air-sea boundary. Waves generated in wind-water tanks may differ from those generated at sea in several aspects: (1) the laboratory waves are more nearly one-directional, lacking the space for growing at an angle to the wind. We have noted that at sea waves are nearly non-directional. (2) waves in tanks appear to resemble sine waves more closely than waves at sea. For a sine wave the frequency distribution of slopes is the "opposite" of the normal distribution, with the maximum slopes (at the inflection points) the most probable, and zero slopes the least probable, as illustrated by figure 1. (3) the rigid top of a wind-wave tank may modify conditions considerably. What is ordinarily considered a surface wave is actually an internal wave at the boundary between air and water. The air must participate in this wave motion. Even though the density of air is only $10^{-3}$ that of water, I think the ratio of the thickness of the air column to the wave length must be an important parameter. (4) the effect of slicks, rain, and other naturally occurring phenomena can easily be overlooked in laboratory investigations.

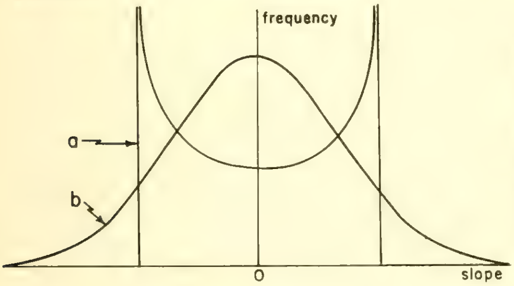


Fig. 1. Frequency distribution of slopes for (a) a single train of sine waves, and (b) a Gaussian sea surface.

In making these points, I do not wish to imply that laboratory investigations are not useful. In fact, notable progress has recently been made through the laboratory investigations by Francis in England, and by Keulegan in the United States. But until direct confirmation can be obtained by measurements at sea, the laboratory results can only be considered as suggestive.

## THE REFLECTION OF RADIO AND RADAR WAVES

In the earlier discussion the tacit assumption was made that reflection from the sea surface is governed by the laws of geometric optics. This will be the case when the water waves are long compared to wave length of the incoming radiation. For light waves we may safely assume this to be true. For radar waves this is no longer the case. The tiny ripples, which are short compared to radar waves, have an entirely different effect than the longer ocean waves. It is interesting, in this connection, that radar sea return from an up-wind direction is definitely stronger than from other directions. Since the overall distribution of slope is nearly independent of wind direction, this shows that the longer waves have directional features which the shorter waves have not. It also suggests that the distribution of slopes is governed largely by very short waves. These examples are quoted to illustrate how studies of the propagation of radar and radio waves can provide additional information about the geometry of the sea surface.

## THE FLUX OF MOMENTUM ACROSS THE AIR-SEA BOUNDARY

The flux of momentum from the atmosphere into the ocean maintains ocean currents and waves. The physical mechanism of this process is not understood. Direct measurements of this flux could be done in the following ways:

1. Reynolds stresses just above the boundary
2. Stresses at the boundary
3. Reynolds stresses just beneath the boundary.

Hot wire anemometry has now been perfected to the point where Reynolds stresses have been successfully measured over land. The method has not yet been used from a vessel. The instrument problem is to achieve a sufficiently high frequency response so that all turbulent elements essential to the momentum flux are included in the measurements. I am not aware of any attempts to measure Reynolds stresses beneath the water surface. This problem deserves considerable attention.

The "wind slope" of the boundary represents one of the oldest and most powerful ways of measuring stresses at the boundary. This involves, however, certain assumptions, and the method is not quite as straightforward as one would wish. A suggestive set of measurements have recently been conducted by Van Dorn. By recording the difference in up and downwind water level along an 800 foot basin to an accuracy of 0.1 mm, he achieved laboratory precision under natural conditions. His results, in general, confirm Keulegan's laboratory work. They indicate that at low wind speeds the transfer is due principally to viscous stresses across a very thin laminar boundary layer; at high wind speeds, the transfer results mainly from the difference in pressure on the windward and lee sides of little waves. In order for the latter process to be operative, the turbulent wind just outside the laminar boundary layer must exceed the velocity of the waves. The effect of a detergent spread on the water is to greatly suppress the little waves and the normal stresses associated with them. The stress increases somewhat during a hard rain.

Van Dorn's results indicate therefore the existence of two processes of about equal importance. They will have different effects on waves and currents, and they should be studied separately. Would it not be possible to measure directly the shear in the laminar boundary layers, both above and beneath the surface? Can methods be devised for measuring the pressure difference across the little waves?

## DISCUSSION

The principal need, I believe, is for measurements whose interpretation does not depend on any preconceived theory. Two types of measurements suggest themselves. One type can give information in great detail about the individual roughness elements of the boundary, and of motion very close to the boundary. The other can give statistical descriptions of the processes involved. The study of the sun's glitter, and of reflection of other electro-magnetic waves from the sea surface, falls into the second category. Further work along the former line is contemplated by Van Dorn, and along the latter line by Duntley, Burt and Sekera.

I have considered only a few limited examples of the general problem concerning the exchange of energy and other properties across the air-sea boundary. These have been chosen not because they are the most important, but because they are the ones with which I am familiar. An excellent outline of the general problem was given by Montgomery at M.I.T. only a year ago.

## DISCUSSION: R.O. Reid

Solar radiation, with the major part of its energy concentrated at relatively short wave lengths, including the visible part of the spectrum of electro-magnetic radiation, is essentially transmitted through the atmosphere or reflected and scattered back to space by clouds and land-sea surfaces. Only a small portion is actually absorbed by the atmosphere. However, the ocean absorbs, within the upper 50 meters, virtually all of the short wave energy which reaches the sea surface (excluding that which is reflected). The ocean, although being a good absorber by virtue of its great mass and a good photosynthetic producer, is a poor heat machine, being unable to develop within itself sufficient power to sustain the circulation of the waters. Instead the ocean returns nearly all of the radiative energy it receives, per unit time, to the sea surface, where it is liberated to the atmosphere essentially as long wave radiation and latent heat -- forms which the atmosphere is readily capable of absorbing and utilizing in its comparatively efficient heat machine cycle. The thermal energy thus converted to mechanical energy in the atmosphere is partially fed back to the ocean by momentum transfer across the sea surface.

The amount of energy which is finally returned to the ocean as mechanical energy in this intricate feed back-counter feed back mechanism is actually but an insignificant portion of the original energy which is received by the ocean from the sun (from 1/10,000 to 1/1,000). Nevertheless this continual supply of energy in the form of "directed" kinetic energy is necessary and sufficient to account for the generation and maintenance of surface waves and the quasi-permanent circulation of the ocean in the presence of a continuous process of kinetic energy degredation by turbulence and ultimately by viscosity.

It is not difficult to see the need for adequate instrumentation capable of procuring basic information on air-sea boundary processes, for the sea surface is apparently the valve controlling the supply of energy for atmospheric storms and in turn is a controlling link in the return of some of this energy utilized in the generation and maintenance of ocean waves and currents. The theory of generation and maintenance of waves and currents by wind is based in part upon knowledge of mometum transfer from air to sea; while computations of the supply of energy to atmospheric storms are in large measure dependent upon latent heat transfer and back radiation. Consequently, ultimate improvement in methods of prediction of waves, storm tides, currents, upwelling, and genesis of storms in the atmosphere rests in no small measure on the validity of the fundamental concepts involved in the theories of boundary transfer processes.

## FORMS OF ENERGY TRANSFER

In summary, there are presumably four important forms of energy transfer which occur at the sea surface. These are, in order of their magnitude:

(1) Radiative transfer
   Transmission, absorption and reflection of solar short wave radiation
   Emission and absorption of long wave radiation
(2) Latent heat transfer
   Evaporation (upward flux of heat)

Condensation (downward flux of heat)

(3) Sensible heat transfer
Conduction toward or away from the surface in the thin laminar layer (if such exists, on the air side of the sea surface) and convection in the turbulent air above. (Some sensible transfer is effected also by spray, salt flux, precipitation, solution of gases from the air, etc.)

(4) Kinetic energy transfer
Associated with momentum transfer from air to sea.

In addition to the transfer of energy, the transfer of mass across the sea surface is important. The transfer of moisture, inseparably associated with the transfer of latent heat, is important in its own right. In addition, the transfer of salt particles to the air is important to the moisture cycle of the atmosphere, as Woodcock and others have shown. The upward flux of salt within the water would perhaps help shed some light on this problem. Finally, absorption of gases at the sea surface, especially oxygen, is of significance to the life cycle of the sea.

## METHODS OF MEASUREMENT

The direct flux of sensible heat, vapor, and momentum by turbulent processes can be shown to be given by the following formulas:

(1) Flux of sensible heat $= \rho c_V \overline{w'\vartheta'}$,

(2) Flux of moisture $= \rho \overline{w'q'}$,

(3) Flux of x-directed momentum (shear stress in the x-direction) $= \rho \overline{w'u'}$,

(4) Flux of salt $= \rho \overline{w's'}$,

where $\rho$ is the density of the fluid, $c_V$ is the specific heat at constant volume of the fluid (air or water, depending upon which medium is investigated with respect to the flux of heat), $u'$ is the eddy component of horizontal velocity in the x-direction or anomaly of velocity from the mean value $\overline{u}$ over a time interval T, $w'$ is the anomaly of vertical velocity from the mean value $\overline{w}$ over the time interval T, $\vartheta'$ is the anomaly of temperature, $q'$ is the anomaly of specific humidity, and $s'$ is the anomaly of salinity of the water. The bar over the top of the various products indicates an average for the time interval T, i.e.

$$\overline{u'w'} = \frac{1}{T}\int_{t-T/2}^{t+T/2} u'w'\,dt,$$

where
$$u' = u-\overline{u},$$
and
$$w' = w-\overline{w}$$

Each pair of quantities $\vartheta'$ and $w'$, $q'$, and $w'$, $u'$ and $w'$ must be observed simultaneously at a given point and must represent anomalies from means evaluated for a common time interval in order that accurate values of flux are obtained from their mean products. The time interval T which is chosen as the averaging interval for $\vartheta$, $q$, $u$, and $w$, as well as for the products $\vartheta'w'$,

$q'w'$, $u'w'$, and $s'w'$ depends upon the situation. The interval must be long enough that consistent values of the mean products are obtained, but yet not so long that time trends of the fluxes of the different quantities are eliminated. The quantity $T$ itself is one of the unknowns to be ascertained experimentally.*

One of the prime factors to be considered in the design of an instrument which will yield satisfactory information for the determination of eddy flux in addition to stability is its time response characteristics. The instrument must be capable of responding to fluctuations having periods much less than the interval $T$. More specifically, the instrument should have a $\tau$ factor (i.e., the time interval corresponding to a response of the instrument of $1/e$ of a sudden change impressed upon it) which is considerably less than the period of those fluctuations associated with the largest amplitude. Temperature is one quantity for which suitable instruments can be devised. However, velocity and especially humidity or salinity present a more formidable problem to the oceanographic or meteorological instrument designer. In some cases, the problem of measuring such quantities can be reduced to one of measuring a temperature, or an electromotive force. Table I contains a brief summary of present instruments or measuring elements capable of yielding a continuous record of the quantities $\vartheta$, $q$, $u$ or $w$, and $s$. Devices for the measurement of radiant flux of energy are also mentioned in this table.

It has been pointed out by Swinbank (1951-b) that, in the interpretation of observed values from any continuous record, the amplitude distortion as well as the phase shift introduced by the imperfect response of the measuring and recording system must be taken into account. For example, if the response characteristics of the humidity device are vastly different from that of the velocity measuring equipment, then the mean products of these quantities will be in error due to the differential distortion and nonsimultaneity introduced by phase shift. This effect will be most pronounced for the short period fluctuations.

The above source of error can be minimized by reducing the response factor $\tau$ to as low a value as is possible. An alternative procedure is to adjust the measuring systems for a given pair of parameters to be utilized in a flux determination such that each system has the same $\tau$ factor, provided that this factor is less than the period of the greatest amplitudes of fluctuations.

Table I is by no means intended as a comprehensive review of possible instruments for measurement of the fluctuations desired, but at least it indicates the possibility of eddy flux measurement over the water. Indeed, Swinbank has demonstrated that such measurements are possible over land.

---

* - It is surmised but not definitely established that a "plateau" in the realm of microscopic turbulence exists which would allow the establishment of averages which are not too sensitive to the interval of averaging (within certain bounds). Indeed it is just such a "plateau", between the microscopic and microscopic, which underlies the science of thermodynamics.

TABLE I: SUMMARY OF INSTRUMENTS CAPABLE OF RECORDING CONTINUOUSLY

| Parameter Sought | Instrument Or Measuring Element | Principle | Probable Error (Approx) | Time Response Factor | References |
|---|---|---|---|---|---|
| Temperature | thermocouple | thermoelectric effect of dissimilar metals, e.g. cu-const. | ± 0.1°c or less | 0.2 to 0.3 sec*<br>*element and recorder system | Anderson and Heibeck (1951)<br>Bellaire and Anderson (1951)<br>Swinbank (1951-a) |
| | thermistor bead | sensitivity of electrical resistance to temperature change | ± 0.1°c or less | #24: 1.1 sec<br>#30: 0.3 sec<br>#36: 0.2 sec<br>each at 10 mph | Anderson and Heibeck (1951) |
| | thermistor rod | ditto | ± 0.4°c or less | 0.9" by 0.4": 1.6 to 2.4 sec | Staley (1952) |
| Humidity | thermocouple psychrometer | wet bulb temperature-thermocouple with a wick | ± 0.1°c above 1 mph | 0.3 sec. | Bellaire and Anderson (1951)<br>Swinbank (1951-a)<br>Swinbank (1951-b) |
| | ditto | thermocouple without a wick | ± 0.1°c (30 sec cycling from water to air) | 2.7 sec | Jehn (1949) |
| | dew-point hygrometer | temperature of a mirror maintained at dew-point temperature by photoelectric relay | ± 0.25°c | probably less than 2 sec | Barrett and Herndon Jr. (1951) |
| | refractometer | measurement of refraction coefficient or dielectric factor by beat | probably less than | 0.2 sec | Crain and Gerhardt (1950)<br>Crain (1948) |

# TABLE I CONTINUED:

| Parameter Sought | Instrument Or Measuring Element | Principle | Probable error (Approx) | Time Response Factor | References |
|---|---|---|---|---|---|
| Humidity | refractometer | frequency principle - temperature must be measured simultaneously | ± 0.2 mbs | 0.2 sec | Crain (1950)<br>Tolbert and Straiton (1950) |
| | hygrograph (not recommended for flux determination) | moisture sensitive membrane | ± 5% rel. hum. | Several minutes or more | |
| Velocity | hot wire anemometer | cooling action of fluid passing over heated element - change of electrical resistance | percent error proportional to speed | about 0.2 sec at 1 mph for .001" plat. wire | Swinbank (1951-b)<br>Ower (1949)<br>King (1914) |
| | hot thermistor bead | ditto | ditto | | |
| | electromagnetic (measurements in sea water)* | measurement of electrical potential set up in a fluid passing through a magnetic field | | probable less than 0.1 sec primarily (lag of recording equipment) | Lonquet-Higgins and Barger (1946)<br>Williams (1930)<br>von Arx (1950) |
| Salinity | conductrometric instrument | conductrometric | ± 0.5% or less | probably less than 0.1 sec | Jacobson (1948)<br>Blake (1945)<br>Blake (1947) |
| | oscillometric* | utilizes principle of radio frequency absorption which depends upon ionic concentrations | | ditto | Leiscester and McCourt (1948) |

TABLE I CONTINUED:

| Parameter Sought | Instrument Or Measuring Element | Principle | Probable Error (Approx) | Time Response Factor | References |
|---|---|---|---|---|---|
| Radiation | Eppley pyrheliometer (short wave) | difference in temperature of surfaces of different absorptivity measured by thermopile | ± 1.5% | that of thermopile recorder system | Kimball and Hobbs (1923) |
| | long wave sensitive radiometer | ventilated flate plate radiometer | – 4% or less | 4 sec | Gier and Dunkle (1951) |

* Instrument not developed or in development stage

## DISCUSSION: A.H. Woodcock

John Isaacs has reminded us of the fundamental fact that oceanographic instruments are, in effect, extensions of our sense organs, and that these instruments aid us in constructing and testing our mental models of the ocean. The trend in this process of model building and testing is toward more complex devices for making measurements. I would like to point out, however, that the air-sea boundary region is one area of ocean study in which the sense organs can be used directly to obtain a qualitative "mental model" of some of the small scale motions which occur. These motions are revealed by living and non-living "instruments" found immersed in the air and sea: birds, fog, smoke, seaweed, plankton.

Qualitative studies of the nature of some of the motions in the sea and air, as revealed by the naturally occurring "instruments", have already been made and published. There is a real need, however, for instruments designed to test quantitatively the indicated motions, and to aid us thereby in judging their probable significance in the transfer of properties between air and sea. A few brief remarks about the apparent nature of the air and water motions are given below.

## WATER MOTIONS NEAR THE SEA SURFACE

Over much of the Western North Atlantic Ocean and during most of the year surface waters contain the floating algae Sargassum. This plant indicates that during winds of force 3 or more surface waters converge in lines lying parallel to the wind direction. During strong winds, descending currents under these convergence lines draw the positively buoyant plants beneath the surface. During winds less than about force 3 the plants converge in "patches" or "islands", suggesting a columnar region of descent of surface waters. Tests of the rates of rise of Sargassum plants indicate that descending motions in excess of 4 to 7 centimeters per second must on occasion exist under the lines of convergence.

The existence of the columnar or linear regions of convergence can be readily tested with simple drift bottles, provided a small boat is used which will not seriously disturb the natural small-scale motions of the surface waters. My drift bottle studies in the Gulf of Mexico were made from a twelve foot dinghy. Drift bottle tests in a force 3 wind among lines of convergence showed an average descent of surface water beneath the lines of one cubic meter per meter length of line for each three minute time interval.

## AIR MOTIONS NEAR THE SEA SURFACE

Over a large part of the Western North Atlantic there is a flow of sensible heat from the sea to the atmosphere. The lower air, thus heated, tends on occasion to rise in a patterned fashion. The form of this ascent varies with wind speed, being columnar during lower speeds and linear with higher speeds. The pattern of this air motion and its change of form with wind speed has been indicated by the soaring flight performance of sea birds, by smoke, and by steam fog in cold air overlying warm seas.

## DISCUSSION AND CONCLUSIONS

Thus there is some evidence that the exchange of properties across the sea-air interface occurs in the presence of a continuous patterned removal of the bounding fluid surfaces, to unknown heights or depths. It has been suggested that these motions in water bring about the formation of the mixed surface layers which often extend many meters in depth. In the air it seems probable that these motions are important in forming the layer of nearly constant potential temperature and mixing ratio which commonly extends in some regions of the North Atlantic from the sea surface up almost to cloud base. Large sea-salt particles, originating in "white caps", and having settling rates of 1 to 20 centimeters per second are also found well distributed in this sub-cloud layer. A vigorous overturning of this layer of air is thus indicated.

Observations such as those briefly indicated above give a qualitative indication of the form and some of the rates of the fluid motions in the air-seaboundary region. These motions are probably a result of the transfer of properties between the sea and the atmosphere. Instruments, capable of measuring the various properties of the fluids which are being continuously removed upward and downward from the air-sea interface, should contribute largely to our understanding of this important boundary. It is my opinion that new instruments are required which are realistically designed to make measurements and to obtain samples within specific and rather limited areas of the fields of fluid motion indicated. In the sea, measurements of the temperature, salinity, velocity, oxygen and perhaps plankton content of descending waters should be made under the areas of convergence. In the air, measurements of temperature, water vapor, velocity and sea salt content in the ascending regions are needed. Measurements such as these seem essential in order to test the reality of the motions apparently delineated by the sea birds and the Sargassum, and in evaluating their possible role in the transfer of properties between the sea and the air.

DISCUSSION: R.B. Montgomery

It may be of interest to supplement Dr. Munk's paper with an account of the present position of the study of evaporation from the ocean, especially since this study cannot proceed without the development of suitable instrumentation. What is presented about evaporation has application to (sensible) heat transfer also, as the transfers of momentum, water, and heat are closely related, but heat transfer is usually less important and more complicated.

During the 1920's and early 1930's, an effort to learn about evaporation from the ocean was made by maintaining evaporation pans in gimbals on research ships (e.g., "Carnegie," "Meteor," "Atlantis"). The observations so obtained have not served any purpose. It is now realized that pan evaporation does not determine the evaporation from natural surfaces, whether water, ground, or vegetation.

A way to measure evaporation from the ocean is not yet at hand, but in my opinion we are now in a position to see how to develop a satisfactory method. In a preliminary form, this method has already been used by Jacobs (1942) to calculate climatological evaporation from climatological values of winds and temperatures over the ocean, but so far we have no reliable check on the constants he used and on other details.

This method depends on the apparent fact that unit-area rate of evaporation, E, is primarily a function of two quantities, the specific-humidity difference between the sea surface and some suitable height, $\Delta q$, and the wind speed at some suitable height, u,

$$E = f(\Delta q,\ u).$$

The function is more or less of the simple form

$$E = \text{const.}\,\Delta q\ u.$$

The function depends to lesser degree on other quantities, such as the temperature difference and the two heights.

As interfacial stress and evaporation are closely related phenomena, and as Munk reports Van Dorn to have found a simple relation between stress and wind we might expect evaporation to be a simple function of wind. Further new evidence comes from the studies at Lake Hefner in Oklahoma. I have been privileged to hear about the results, as yet unpublished, from G. Earl Harbeck, Jr. (Geological Survey), E.R. Anderson, and J.J. Marciano at U.S. Navy Electronics Laboratory, San Diego. Comparison of measured daily evaporation from Lake Hefner with meteorological measurements supports the simple linear function.

The Lake Hefner formula, however, should not be assumed to apply to the ocean. To find oceanic evaporation, two steps are required: (1) The difficult step of making sufficient measurements of E, $\Delta q$, u, and other quantities to determine the evaporation formula. (2) The easier step of using this formula to calculate evaporation from $\Delta q$, u, etc.

The only method so far suggested for measuring evaporation from the ocean is that of measuring the eddy flux of aqueous vapor a short distance above the interface. The unit-area flux is $\langle \rho v_z q \rangle_{Av}$, where $\rho$ is air density and $v_z$ is the upward component of velocity. This flux has been successfully measured over land by Swinbank (1951) by use of a hot-wire anemometer and thermocouple thermometers. Probably his method cannot be used over the ocean without modificiation, but presumably a means can be found. This is the place where instrumentation is needed.

With regard to the second step, existing observations of wind, humidity, and interfacial temperature, although very numerous, may not be adequately accurate or suitable except in special cases. The weather-ship observations, made regularly at fixed positions, can be expected to provide the most useful data. Perhaps a special program will be required to obtain suitable observations from research ships and other selected ships. (An attempt to include such observations in the bathythermograph program was early abandoned).

Although the way seems clear, the study of evaporation is now inactive. The reason for this inactivity must be that no great need is felt for knowing the evaporation from the ocean.

## REFERENCES: W. H. Munk

MUNK, W.H. "Origin and Generation of Waves". *Proc. of First Conference on Coastal Engineering, Oct. 1950, pp. 1-4. Reprinted in U.S.N. Civil Engineer Corps. Bull., vol. 6 pp. 133-136,* May 1952.

MUNK, W.H., IGLESINS, H., and FOLSOM, T. "An Instrument for Recorcing Ultra-Low-Frequency Ocean Waves". *Review of Scientific Instruments, Vol. 19, No. 10, Oct. 1948, pp. 654-658.*

MUNK, W.H. and REVELLE, R.R. "Sea Level and the Rotation of the Earth". *Amer. Journal of Science, in press.*

## REFERENCES: Reid

ANDERSON, L.J. and HEIBECK, H.L. 1951. "A Tau-meter for Rapid Response Temperature Recording Systems". *Bull. Am. Met. Soc. Vol. 32, no. 2, pp. 67-71*

BARRETT, E.W., and HERNDON, L.R. JR., 1951. "An Improved Electronic Dew-Point Hygrometer". *J. Met. Vol. 9, no. 1, pp. 40-51.*

BELLAIRE, F.R. and ANDERSON, L.J. 1951. "Thermocouple Psychrometer for Field Measurements". *Bull. Am. Met. Soc. Vol. 32, no. 6, pp. 217-220.*

BLAKE, G.G. 1945. "A device for Indicating Small Changes in Electrolytic Resistance". *J. Sci. Instr. Vol. 22, p. 174.*

BLAKE, G.G. 1947. "Conductimetric Analysis at Radio-Frequency". *J. Sci. Instr. Vol. 24, pp. 101-102.*

CRAIN, C.M. 1948. "Dielectric Constant Several gases at a wave length of 2.2 Centimeter". *Phys. Rev. Vol. 74, pp. 691-693.* 1950. "Apparatus for Recording Fluctuations in the Refractive Index of thr Atmosphere at 3.2 cm Wavelength". *Rev. Sci. Instr. Vol. 21, pp. 456/457.*

CRAIN, C.M. and GERHARDT, J.R. 1950. "Some Preliminary Studies of the Rapid Variations in the Index of Refraction of Atmospheric Air at Microwave Frequencies". *Bull. Am. Met. Soc. Vol. 31, no. 9, pp. 330-335.*

GIER, J.T. and DUNKLE, R.V. 1951. "Total Hemispherical Radiometers". *Trans. Am. Inst. Elec. Engr. Vol. 70, pp. 339-45.*

JACOBSON, A.W. 1948. "An Instrument for Recording Continuously the Salinity, Temperature, and Depth of Sea Water". *Elec. Eng. Vol. 67, p. 455.*

JEHN, K.H. 1949. "Wet Bulb Temperatures Without a Wick". *Rev. Sci. Instr. Vol. 20, no. 9, pp. 668-673.*

KIMBALL, H.H. and HOBBS, H.E. 1923. "A New Form of Thermoelectric Recording Pyheliometer". *J. Opt. Soc. Am. & Rev. Sci. Instr. Vol. 7, no. 9, pp.707-718.*

KING, L.V. 1914. "On the Convection of Heat from Small Cylinders in a Stream of Fluid". *Trans. Roy. Soc. (London). A. Vol. 214, pp. 373.*

LEICESTER, J., and McCOURT, C.F. 1948. "An Apparatus for Measurement and Recording of Density of Aqueous Ionic Solutions". *Report No: A.M.L. (external) no. A/43; Admiralty Materials Lab. 6 pp.*

LONGUET-HIGGINS, M.S., and BARBER, N.F. 1946. "The Measurement of Water Velocity by Electromagnetic Induction". "An Electrode Flow Meter". *Admiralty Research Lab., Teddington Rept. A.R.L./R1/102.22/W,*

OWER, E. 1949. "The Measurement of Air Flow". *3rd Ed. rev. Chapman & Hall, London. pp. 240-270.*

STALEY, R.C. 1952. "Performance Characteristics of Sanborn Rod Thermistors". *Bull. Am. Met. Soc. Vol. 33, no. 2, pp. 67-72.*

## REFERENCES: Reid Cont'd.

SWINBANK, W.C. 1951a. "A Sensitive Vapor Pressure Recorder". *J. Sci. Instr. Vol. 28, p. 86-9.* 1951b. "The Measurements of Vertical Transfer of Heat and Water Vapor by Eddies in the Lower Atmosphere". *J. Met. Vol. 8, no.3, pp135-145.*

TOLBERT, C.W., and STRAITON, A.W. 1950. "A Phase-Shift Refractometer". *Rev. Sci. Instr. Vol. 22, no. 3, pp. 162-165.*

VON ARX, W.S. 1950. "An Electromagnetic Method for Measuring the Velocities of Ocean Currents from a Ship Under Way". *Papers in Phys. Oce. and Met. Vol. II, no. 3, 62 pp.*

WILLIAMS, E.J. 1930. "The Induction of Electromagnetic Forces in a Moving Liquid by a Magnetic Field, and Its Application to an Investigation of the Flow of Liquidx". *Proc. Phil. Soc. London. Vol. 42, pp. 466-487.*

## REFERENCES: A.H.Woodcock

BUNKER, A.F., HAURWITZ, B., MALKUS, J.S., and STOMMEL, H. 1949. "Vertical Distribution of Temperature and Humidity over the Caribbean Sea". *Papers Phys. Oce. and Met. Vol. XI, no. 1. pp. 1-82.*

JACOBS, W.C. 1942. "On the Energy Exchange Between Sea and Atmosphere". *Sears Found. J. Mar. Res. Vol. V, no. 1. pp. 37-66.*

LANGMUIR, IRVING. 1938. "Surface Motion of Water Induced by Wind". *Science. Vol. 87, pp. 119-23.*

WOODCOCK, A.H. 1940. "Convection and Soaring over the Open Sea". *Sears. Found. J. Mar. Res. Vol. III, no. 3. pp. 248-53.* 1944. "A Theory of Surface Water Motion Deduced from the Wind-induced Motion of the Physalia". *Sears Found. J. Mar. Res. Vol. V, no. 3. pp. 196-205.* 1950. "Subsurface Pelagic Sargassum". *Sears Found. J. Mar. Res. Vol. IX, no. 2. pp. 77-92.* 1952. "Atmospheric Salt Particles and Raindrops". *J. Met. Vol. 9, no. 3. pp200-212.*

WOODCOCK, A.H., and WYMAN, JEFFRIES. 1947. "Convection Motion in Air over the Sea". *Wnnals N.Y. Acad. Sci. Vol. XLVIII, art. 8, pp. 749-76.*

## REFERENCES: Montgomery

JACOBS, W.C. 1942: "On the energy exchange between sea and atmosphere". *J. mar. Res., 5, 37-66.*

SWINBANK, W.C. 1951: "The measurement of vertical transfer of heat and water vapor by eddies in the lower atmosphere". *J. Meteor., 8, 135-145.*

# INDEX

- A-frame, 42
- Absorption of gases, 214
- Acoustic characteristics of oceanographic vessels, 125
- Acoustic Instrumentation, 101-122
  - Echo-ranging, 43, 62
    - in measurement of ocean currents, 113, 120
  - Echo-sounding, 5, 39, 109, 197
    - biological sounds classified by sound spectrograph techniques, 114
    - currents, acoustic methods of studying, 30, 113, 120
    - cross correlator, 113
    - deep-scattering layer, 43, 109
    - echo-sounder used as wave meter, 121
    - EDO, 197, 200
    - IBM summary punch, 118
    - NMC, 197, 200
    - SOFAR, 9, 65, 80, 82, 111
    - sound propagation, predicted conditions, 120
    - Telecorder, 118
    - Telereader, 118
  - Nature of acoustic data, 101
  - Passive listening techniques, 102
    - Bell Telephone Laboratory's 5E hydrophone, 103
    - biological sounds, identifying, 106
    - Brush Development Company's AX 58 series hydrophone, 103
    - hydrophone, 103
    - magnetic tape recorder, 63, 105
    - phonograph recorder, 105
    - photographic recorder, 63, 105
    - wire recorder, 105
    - sonagraph, 106
    - SUITCASE, 105
    - vibralyzer, 106
  - Sound transmission studies, 108
    - demolition block, Mark IV, 109
  - Sound transmission studies --
    - depth charge, 109
    - electrical sparks, 108
    - fuels, combustible under water, 108
    - pentolite, 109
    - sirens, underwater, 108
- Acoustic methods of exploring ocean floor, 197
- Admiralty Research Laboratories, 156
- AFFRAY, 200
- Aircraft, in sea-ice studies, 89
- Air-Sea Boundary Processes, 210-221
  - Energy transfer, forms of, 213
    - kinetic energy, 214
    - latent heat, 213
    - radiative energy transfer, 213
    - sensible heat, 214
  - Humidity measurement in, 216-217
    - dew-point hygrometer, 216
    - hygrograph, 217
    - refractometer, 217
    - thermocouple psychrometer, 216-217
    - thermocouple without wick, 216
  - Methods of measurement (and see property measured), 214
  - Radiation measurement in, 218
    - Eppley pyrheliometer (short wave), 218
    - long-wave sensitive radiometer, 218
  - Salinity measurement in, 217
    - conductometric instrument, 217
    - oscillometric instrument, 217
  - Solar radiation, 210
  - Temperature measurement in, 216
    - thermistor bead, 216
    - thermistor rod, 216
    - thermocouple, 216
  - Velocity measurement in, 217

  Velocity measurement in, --
    electromagnetic, 217
    hot-thermistor bead, 217
    hot-wire anemometer, 217
ALBATROSS, 196, 207
Allan Hancock Foundation, 199
Allen phytoplankton bottle, 40
Amplification, 5, 7
Aneroid barometer used as wave meter, 142
Anit-roll devices on oceanographic vessels, 138
Aqualung, 44, 45, 199
Arctic Research Laboratory, 91, 97
Arctic stations in sea-ice studies, 91
ATLANTIS, 124, 200, 220
Audible presentation, 4
Automatic chlorinity titrator (ACT-I) 177, 189
Automatic potentiometric titration apparatus, 177
Automatic reagent dispenser, 186
Automatic servo-operated photometer (ASOP), 183
Auxiliary machinery, 126

Bacteria, sampling of, 39-41, 49
Ball-breaker, 197
Bascom deep-sea instrument station, 142
Bathygraf, 44
Bathyscaphe, 199
Bathysphere, 44, 199
Bathythermograph, 56, 57
  New types needed, 39
  Winch, 196
Beach erosion board step resistance gage, 146, 150
Beckman model DU spectrophotometer, 182
Bell Telephone Laboratory's 5E hydrophone, 103
Benthic organisms, sampling of, 42-43, 50
Benthograph, 44
Benthoscope, 44, 199
Biological Instruments, 36-50
  A-frame, for handling trawl, 42
  Bacteria (and phytoplankton), sampling of, 39-41, 49
  Benthic organisms, sampling of, 42-43, 50
Biological Instruments, --
  Needed instrumentation, 45
  Nekton, sampling of, 41-42, 50
    electrical fishing, 42
    midwater trawl, 41, 50
  Plankton sampling equipment, 37
    Clarke-Bumpus sampler, 38, 48
    Hardy plankton recorder, 35, 47
    hi-speed samplers, 38, 49
  Phytoplankton (and bacteria), sampling of, 39-41, 49
    carbon-14, 41
    molecular filter, 40
  Self-contained diving units, 44, 50
  Sonic devices, 43
  Underwater photography, 44
    bathygraf, 44
    benthograph, 44
Biological sounds
  Classification by sound spectrographic techniques, 114
  Identifying, 106
Bottom Sampling, -- see Ocean Floor, exploration of
Brush Development Company's AX 58 series hydrophone, 103
Brush oscillograph, 78
Bubble-pulse frequency, 74
Bucket and thermometer temperature measurements, 55
Bottom temperature-gradient recorder, 64, 203
BURTON ISLAND, 96
Buoys
  Anchored, as ocean stations, 16
  Drifting, 18
  Marker, 150
  and Navigation, 17
  Long-line damped spar, 142
  Recording or telemetering, 166
  Short-line damped spar, 142

Cable, 196, 205
  Buoyant, 16
  Spherical clamp for, 39
Calibration of chemical instruments, 172
California Institute of Technology, 139
Carbon-14, 9, 41, 82
CARNEGIE, 168, 220

- Centrifugal plankton pump, 38, 49
- CHALLENGER, 10
- Chemical Measurements, 166-193
  - Chlorinity-salinity-density measurements, 167
    - automatic chlorinity titrator, 177, 189
    - automatic potentiometric titration apparatus, 177
    - calibration systems, chemical, 172
    - conductivity-temperature-depth recorder (CTD), 65 66, 171, 186
    - conductivity-temperature indicator (CTI), 173, 186
    - high-frequency oscillators, 177
    - Knudsen method, 167, 187
    - recording salinity meter, 171
    - salinity measurements in air-sea boundary processes, 217
    - salinity-temperature-depth recorder (STD), 172, 186
    - salinometer for brackish water, 174
    - Wenner bridge, 172, 187
  - Colorimeters (and spectrophotometers), 181
    - automatic servo-operated photometer (ASOP), 182
    - Beckman model DU spectrophotometer, 182
    - electric eye photometer (EEP), 183
    - Hehner tubes, 181
    - Wattenberg comparator, 181
  - Concentration techniques, 183
    - chromatographic columns, 184
    - ion exchange resins, 184
  - Polarographic measurements, 185
    - seagoing polarographic instrument, 186
  - Radiochemical measurements, 185
  - Special shipboard devices, 186
    - automatic reagent dispenser, 186
  - Spectrophotometers (and colorimeters), 181
- Chesapeake Bay Institute, The Johns Hopkins University, 30, 166, 169, 175, 182, 183
- Chlorophyll measurements in biological studies, 40, 49
- Chromatographic methods, 7, 193
- Circulation Measurements, 13-30
  - Buoys
    - anchored, as ocean stations, 16
    - drifting, 18
  - Currents, 21-30
    - acoustic methods, 30, 113, 120
    - deep currents, 22
    - electromagnetic methods, 226
    - estuarine, 23
    - geologic problems, 23
    - pitot-type current meter, 21
    - sub-surface current recorders, 140
    - wind-driven surface currents, 21
  - Steady and transient states, 15
- Chlorinity-salinity-density measurements, 167
- Clam shell bucket, 50
- Clarke-Bumpus sampler, 38, 48
- Colorimeters (and spectrophotometers), 181
- Columbia University, 79, 80, 202
- Concentration techniques, chemical, 183
- Conductivity-temperature-depth indicator (CTD), 65, 66, 169, 186
- Conductivity-temperature indicator, (CTI), 65, 66, 169, 186
- Continuous centrifuge, 49
- Cores and Coring -- see Ocean Floor, exploration of
- Cross correlator, 113
- Crystal chronometer, 81
- Current cross, 20, 21

- Dampling disk, in wave recording, 142
- Deep currents, measurement of, 22
- Deep-scattering layer, 43, 109
- Deep-sea pressure recorder, 80
- Deep-sea rock dredge, 195
- Deep-water dredge, 42
- Deep water Mark III wave recorder, 144
- Demolition block, Mark IV, 109
- Depressor, 39, 88
- Depth charge, in acoustic studies, 109
- Depth flow meter, 39

Detergent, effects on water surface, 212
Devik infra red pick-up, 63
Dew-point hygrometer, 217
Direct-reading analytical balance, 167
DISCOVERY, 37
Dredges -- see Ocean Floor, exploration of
Drift bottles, 219
Dye tracers, 96
Dynamometer, 197

Echo-ranging -- see Acoustic Instrumentation
Echo-sounding -- see Acoustic Instrumentation
Echo-type altimeter, 142
EDO Echo-sounder, 197, 200
Ekman grabs, 42
Electric eye photometer (EEP), 183
Electrical cables, installation of, 152
Electrical fishing, 42
Electrical sparks, discharged under water, 108
Electromagnetic measurements of velocity, 217
Electronic gear in sea-ice studies, 92
Electronic-position-indicator, 93
Elutriator, 46
Emery and Champion's scoopfish, 264
Energy transfer -- See Air-Sea Boundary Processes
EPCE(R)857, 72
Eppley pyrheliometer, 218
Estuarine circulation, measurement of, 23
Explosives, 108

Filter photometer, 191
Fluorescein dye, 27
FRAM, 86, 89, 92, 93
Fuels, combustible under water, 108

GALATHEA, 41, 196
Geological problems, in circulation measurements, 23
Geomagnetic electrokinetograph (GEK), 21, 22, 95
Geophysical Measurements, 71
  Seismic reflection, 78
  Seismic refraction, 72
  Seismic refraction, --
    bubble-pulse frequency, 74
    energy spectrum of refracted wave, 73
    hydrophone arrangement, 73
    recording methods, 78
German Hydrographic Institute, 195
Goetz and Tsuneishi Molecular Filter, 40, 192
Grab samplers -- see Ocean Floor, exploration of
Gravity measurement, 72

Hardy plankton recorder, 37, 47
Hehner tubes, 181
Helicopters, 90
Hi-speed samplers, 38, 49
High-speed diving dredge, 207
Holme's bottom sampler, 50
HORIZON, 42, 72, 139
Hot thermistor bead, in velocity measurement, 217
Hot-wire anemometer, 217
Humidity measurements -- see Air-Sea Boundary Processes
Hvorslev-Stetson free-fall corer, 202
Hydrophones
  Directional, 102, 103
  Non-directional, 103
  in seismic refraction studies, 71
Hygrograph, 217

IBM summary punch, 118
Ice -- see Sea-Ice Problems
Inclinometer, recording, 21
International Ice Patrol, 89
Ion exchange resins, 184
Isaacs-Kidd midwater trawl, 41

Juday plankton trap, 48

Kemmer water sampler, 48
KERSTIN, 206
Knapp bottom pressure gage, 149
Knudsen method, 167, 187
Kort Nozzles, 125
Kullenberg piston corer, 42

Lamont Geological Observatory, Columbia University, 81, 82, 196, 199, 200, 202
Listening -- see Acoustic Instrumentation
Long-wave sensitive radiometer, 218
Loran stations, 92
Lumetron model 402-E photometer, 182

Magnetic tape recorder, 105
Magnetostriction, 7
Magnetometer, 81
Malkus bathypitotmeter, 21
Marine galvanometer, 166
Maritime Commission, 123
Mark I deep water wave recorder, 143
Mark II deep water wave recorder, 143
Mark V shore wave recorder, 148
Mark VI shore wave recorder, 148
Mark VIII shore wave recorder, 148
Mark IX shore wave recorder, 146, 147, 155
Mark IX telephone telemetering receiver, 155
Massachusetts Institute of Technology, 213
MAUD Expedition, 94
METEOR, 220
Microbarovariograph, 80
Miller oscillograph, 78
Molecular filter, 40, 189
Micro-oceanographic gear, 66
Midwater trawl, 41, 50
Mimeograph paper, used in water current studies, 27

Nansen bottle, 40, 52
National Bureau of Standards, 172
National Research Council, 133
NAUTILUS, 87, 96
Navigational electronic gear, 86
Nekton, sampling of -- see Biological Instruments
NEL snapper, 195
NMC echo-sounder, 197, 200

Ocean Floor, Exploration of, 194-209
    Acoustic methods, 197
    Acoustic methods, --
        ball-breaker, 197,
    Bottom temperature-gradient recorder, 39, 208
    Coring, 194
        Hvorslev-Stetson free-fall corer, 202
        Kullenberg piston corer, 42, 194
        preservation of cores, 207
        12-24 inch diameter core, 205
    Direct sampling, 194
    Dredges, 195
        clam shell bucket, 50
        deep-sea rock dredge, 195
        deep-water dredge, 42
        high-speed diving dredge, 207
        orange peel dredge, 50
        pipe dredges, 196
    Grab samplers, 42, 195
        Ekman grabs, 42
        NEL snapper, 195
        Peterson grab, 42, 195
        Ross snapper, 42
        snappers, 42, 195
        Holme's bottom sampler, 50
    Underway samplers, 195
        Emery and Champion's Scoopfish, 195
        Pratje underway sampler, 195
        Worzel's BT sampler, 195
    Winches, 196
    Wire rope, 196, 205
    Visual methods, 198
        self-contained diving units, 199
        underwater photography, 199
        underwater television, 199
Oceanographic Instrumentation, Considerations of, 1-12
    Characteristics of human senses, 4
    Collecting instruments, 6
    Effect of sea on instrumentation, 8
    Experience and understanding, 1
    Instruments and development of knowledge, 2
    Measuring instruments, 7
    Mental models, 3
    Non-transforming samplers, 6
    Presentation of information, 1
    Sensing elements, 7

- Transforming samplers, 7

Oceanographic Vessels, Considerations of, 123-138
- Acoustic characteristics of, 125
- Anti-roll devices, 138
- Auxiliary machinery, 126
- Control of, 128
- Main engines, 126
- Need for, 123
- Oceanographic equipment, 127
- Oversize rudder, research vessel, 125
- Performance and design specifications, 127
- SUITLAND, 129
- Type of, 124
- Winches, 127

Orange peel dredge, 50
Oscillators, high frequency in chemistry, 186
Oscilloscope, 5

Parrack and Jensen recording salinity meter, 180
Passive listening -- see Acoustic Instrumentation
Pentolite, 109
Peterson grab, 42, 195
Phonograph recorder, 105
Photographic recorder, 63, 105
Phytoplankton, sampling of -- see Biological Instruments
Pier-mounted gages, 149
Pipe dredges, 196
Pioto-type current meter, 21
Plankton sampling equipment -- see Biological Instruments
Plankton sorter, mechanical, 46
Plastic bottles for water samples, 98, 167, 189
Polarographic measurements, 185
Photography in sea-ice studies, 91
Photography, underwater, 9, 199
- Bathygraf, 44
- in biological studies, 44
- Benthograph, 44
- Commercial cameras, 44
- in ocean floor studies, 29
- Remotely operated camera, 44
- Salt-ballasted cameras, 88
- E.N. Thorndike camera, 205

Pratje underway sampler, 195
Precision thermistats, 167
Psychrometer, 216
Purse seining, mid-depth, 50

Radar, 91, 217
Radiation measurements -- see Air-Sea Boundary Processes
Radiochemical measurements, 185
Rayleigh disk, 140
Reagent dispenser, automatic, 186
Recording methods in refraction studies, 78
Recorder
- Magnetic tape, 63, 105
- Phonograph, 105
- Photographic, 63, 105
- Unattended, 18
- Wave -- see Wave Measurements
- Wire, 105

Recording inclimometer, 21
Reflection measurements, 72
Refraction measurements, 79
Refractometer, 217
Reversing thermometers, 56
- Reliability of, 68

Ross snapper, 42

Salinity measurements -- see Chemical Measurements and Air-Sea Boundary Processes
Salinity-temperature-depth recorder (STD), 1, 168, 186
Salinometer for brackish water, 170
SAN PABLO, 128
Seagoing polarographic instrument, 167, 168
Sea-Ice Problems, 85-100
- Facilities for sea-ice studies, 86
  - arctic stations, 91
  - aircraft, 89
  - land and ice vehicles, 91
  - submarines, 88
  - supporting electronic gear, 92
  - surface vessels, 86
- Interactions of ice and bounding Media, 94
- Physical and chemical properties of sea ice, 93

Sediment traps, 208
SEDOV, 86
Seismic methods in sea-ice studies, 90
Seismic reflection, 78
Seismic refraction, 72

Seismograph, 79
Self-contained diving units,
  in biological studies, 44, 50
  in ocean floor studies, 199
Servo-systems, 62
Shoran, 92
Sirens, underwater, 108
SKIJUMP, project, 90
Snappers -- see Ocean Floor, exploration of
SOFAR, 9, 65, 80, 82, 111
Sonagraph, 106
Sonic devices in biological studies, 43
Sonic radio-link spar buoy wave height meter, 143
Sound propagation predicted conditions, 120
Sound transmission studies -- see Acoustic Instrumentation
SPENCER F. BAIRD, 128
Spectrophotometers, 184
Spherical cable clamp, 39
Steady and transient states in oceanic circulation, 14
Stereophotographs, 21
Submarines, in sea-ice studies, 88
Sub-surface current recorders, 140
SUITCASE, 105
SUITLAND, 129
  Deck, 131
  General characteristics, 129
  Ice-breaking ability, 132
  Propulsion, 132
  Rigging, 129
  Sounding well, 131
  Superstructure, 131
  Winches, 131
Surface vessels, in sea-ice studies, 86
Suspended underwater pressure recorders, 143

Telecorder, 118
Telemetering, 17, 20, 28, 79, 155
Telereader, 118
Television, underwater, 44
Temperature-Measuring Instruments, 55-69
  in Air-Sea Boundary Processes, 225
  Design of, 62
  Errors in temperature data, 60
  Needed temperature recorders, 63
Temperature Measuring Instruments --
  Older instruments, 55
    bathythermograph, 56
    bucket and thermometer, 55
    reversing thermometers, 56
    water intake thermometers, 56
  16-channel temperature recorder, 65
  Temperature-profile-recorder (TPR), 65
  Thermal measuring problems, 58
  Thermal sensitive devices, 62
  Under development, 63
Texas A. and M., 67, 171, 177
Thermal element, dynamic size of, 61
Thermal measuring problems, 58
Thermal response factors, 66
Thermal sensitive devices, 62
Thermistor bead, 216
Thermistor rod, 216
Thermitow, 63
Thermocouple, 216
  Psychrometer, 216
    without wick, 216
Thermometric depths, accuracy of, 68
Tide gauge, 14, 25, 80, 170
TNT, 108
Tonolli plankton bar, 49
Towed gravimeter, 81
Trans-Pacific expedition, 43
Trawl
  Bottom, 207
  Isaacs-Kidd midwater, 41
  Midwater, 50
  Otter, 41, 50
Tripartite wave recorders, 141
Tsunami recorders, 80
Turbidity current instrumentation, 23

Underway samplers -- see Ocean Floor, exploration of
U.S. Coast and Geodetic Survey, 93, 110, 197
U.S. Coast Guard, 132, 151, 168
U.S. Naval Ordnance Laboratory, 150
U.S. Naval Station, 149

- U.S. Navy Electronics Laboratory, 63, 65, 97, 112, 168, 195, 197, 199, 221
- U.S. Navy Hydrographic Office, 86, 125
- U.S. Navy Radio and Sound Laboratory, 143
- U.S. Navy Underwater Sound Laboratory, 114, 118
- University of California, Berkeley, 139
- University of California, Scripps Institution of Oceanography, 1, 10, 41, 63, 79, 128, 139, 155, 177, 197
- University of Southern California, 44
- University of Washington, 66

- Vacuum Filtering, 40
- Vapor pressure thermometers, 62
- Velocity measurements -- see Air-Sea Boundary Processes
- Vibralyzer, 106
- Vidicon tube, 200

- Water intake thermometers, 56
- Water sampler
  - Automatic, 46
  - Kemmerer, 40
  - Nansen bottle, 40, 56
  - Plastic bottles, 98, 167, 189
- Waterways experiment station, 158
- Wattenberg comparator, 181
- Wave tanks, studies in, 211
- Wave Measurements, 139-165
  - Analysis of records, 154
    - for height, 154
    - for period, 156
  - Analysis of sub-surface pressure records, 157
  - Aneroid barometer used as shipboard wave meter, 142
  - Bascom deep-sea instrument station, 142
  - Deep-sea pressure recorder, 80
  - Deep water, 142
  - Correction for motion of spar buoy, 142
    - long line damped spar buoy, 142
    - recorders used with spar buoy, 143
  - Correction for motion of spar buoy --
    - short line damped spar buoy, 142
    - sonic radio-link spar buoy, a wave height meter, 143
    - suspended underwater pressure recorders, 143
  - Direction, 139
    - sub-surface current recorders, 140
    - tripartite wave recorders, 141
  - Gravity, 145
    - Beach erosion board step resistance gage, 146
    - Knapp bottom pressure gage, 149
    - Mark V shore wave recorder, 148
    - Mark VI shore wave recorder, 148
    - Mark VIII shore wave recorder, 148
    - Mark IX shore wave recorder, 147
    - Woods Hole shore wave recorder, 147
  - Installation of recorder, 149
    - electrical cables, installation of by small craft, 153
    - electrical cables, installation of, 152
    - marker buoys for sub-surface pressure gages, 151
    - pier mounted gages, 149
    - selecting site, 149
    - tripods for sub-surface pressure gages, 150
  - Long period, 144
    - deep water Mark III wave recorder, 144
    - Tsunami recorder, 145
  - Wave meter, substitution of inverted echo-sounder for, 121
- Wenner bridge, 177, 187
- Winkler titration, 185
  - Bathythermograph, 196
  - Deep-sea, 131
  - Hydrographic, 131
  - in ocean floor studies, 196
  - for oceanographic vessels, 131
- Wind-driven surface currents, measurements of, 21
- Wire recorder, 105

Wire rope, in ocean floor studies, 196, 205
Woods Hole Oceanographic Institution, 20, 28, 48, 50, 63, 79, 82 123, 133, 147, 158, 168, 199
Woods Hole shore wave recorder, 147
Woods Hole tripod as mounting for wave meter, 150
Worzel's BT sampler, 195